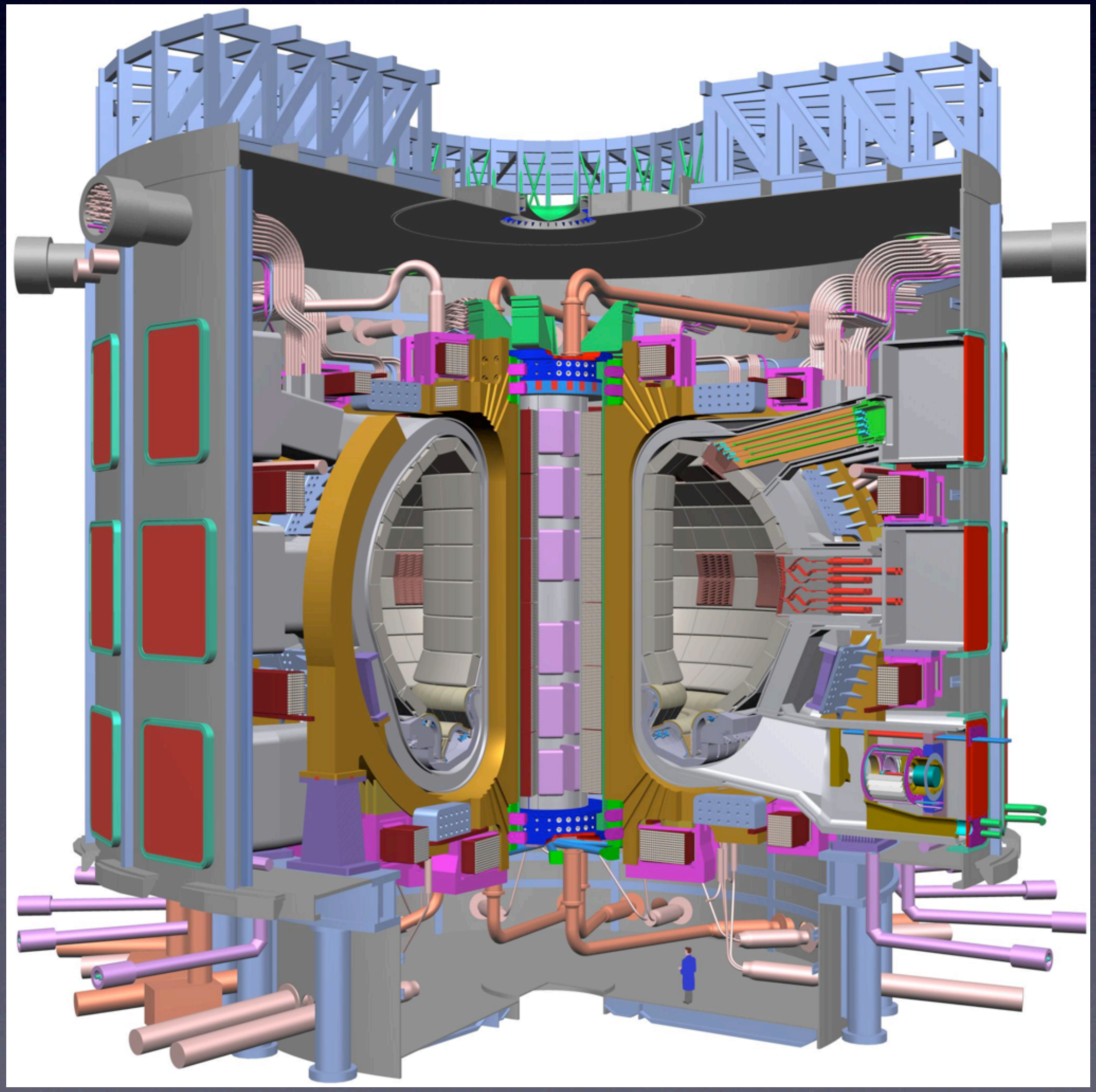
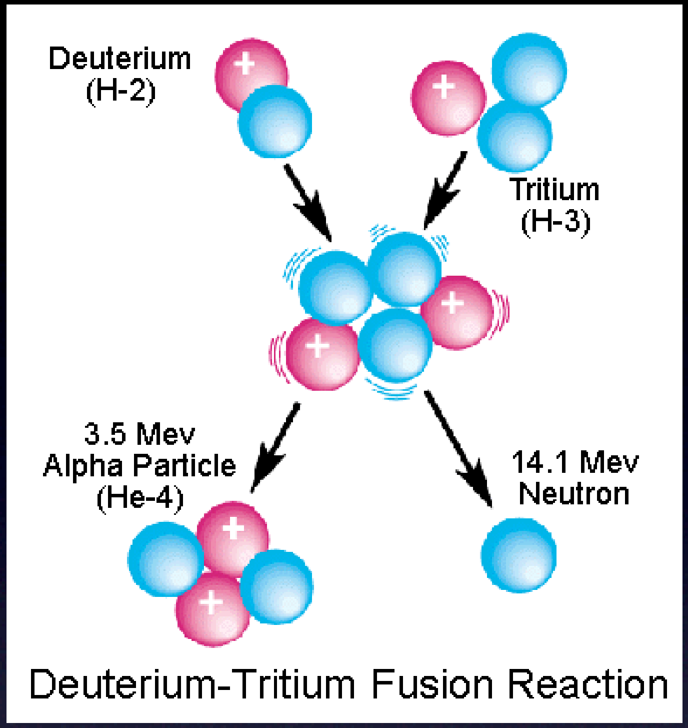
Why is ITER so darn big?
(or Turbulence and Transport in Magnetized Plasmas)

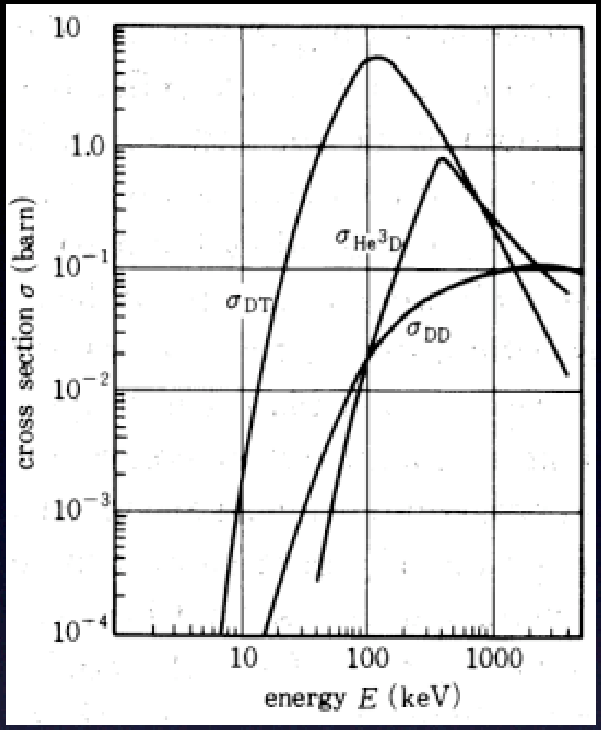


Troy Carter
Dept. of Physics and Astronomy
UCLA

LANL Plasma Physics Summer School Lecture
August 1, 2006

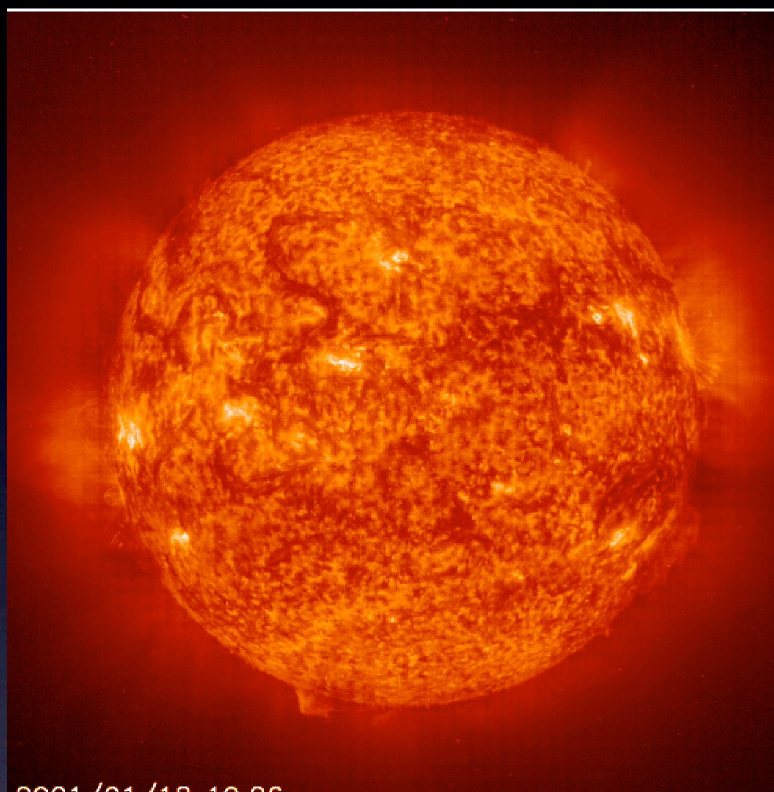
Reminder: Fusion energy only effecient with confinement

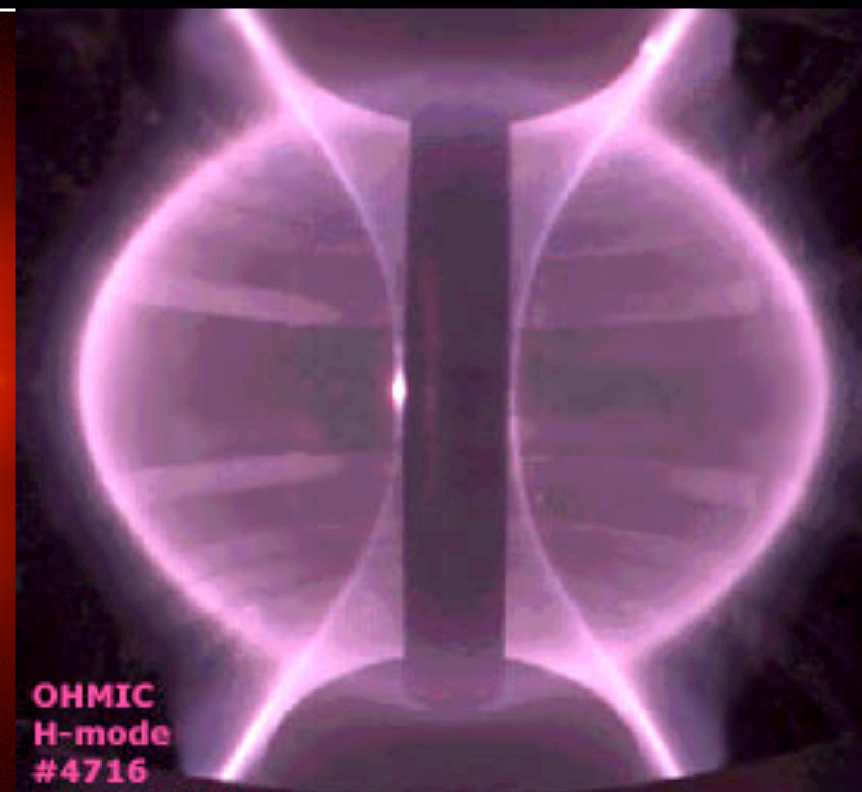


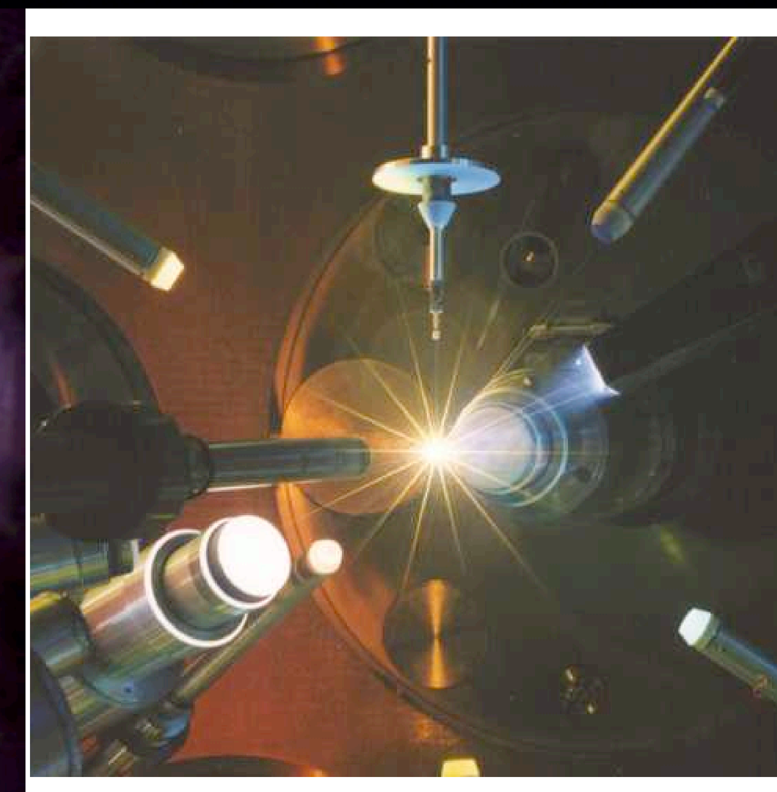


- Coulomb barrier makes cross-section appreciable only at moderate energy
- Scattering cross-section >> fusion cross-section (beam fusion will not work)
- Need to confine a hot plasma to allow multiple scattering collisions per fusion (thermonuclear fusion)

Thermonuclear fusion in a hot, confined plasma

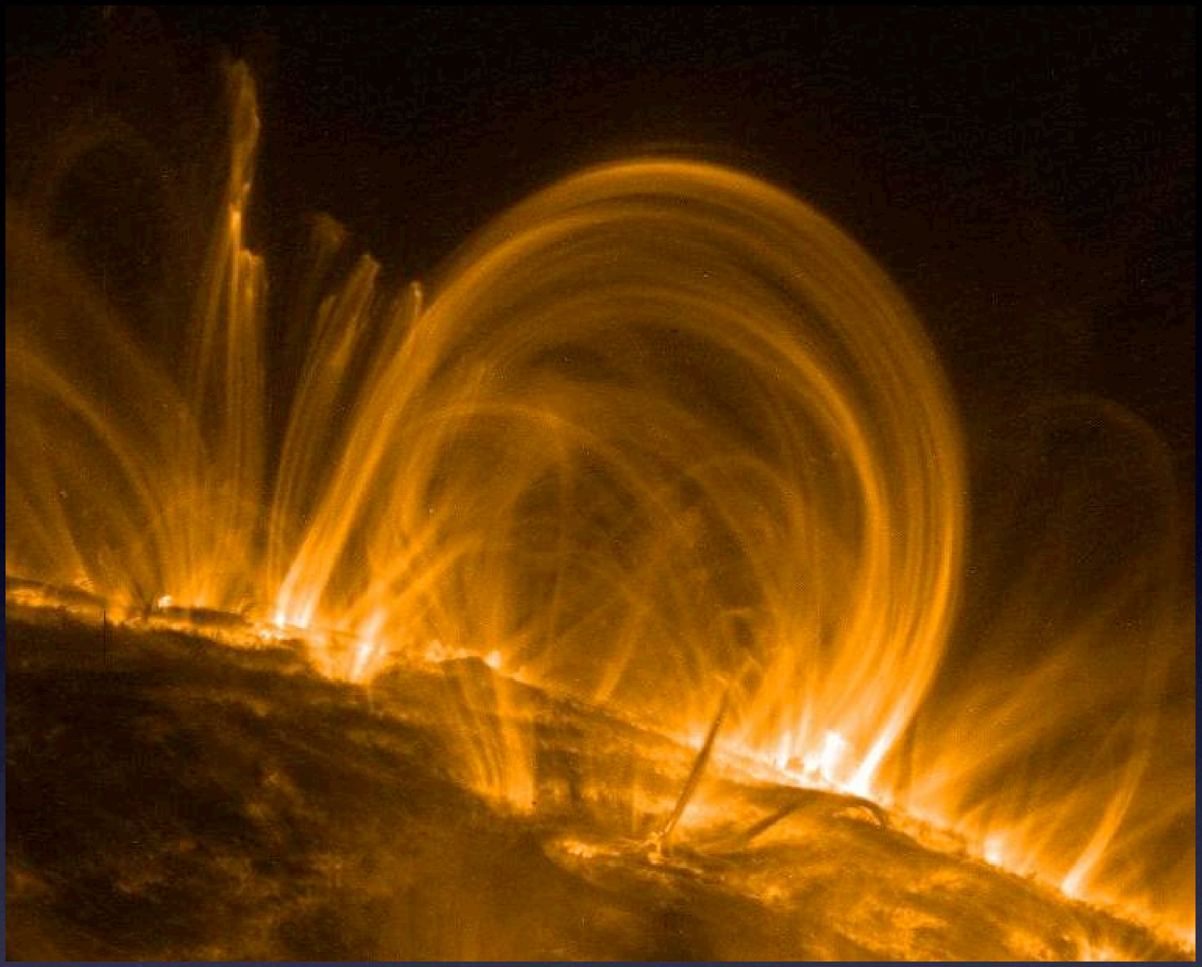


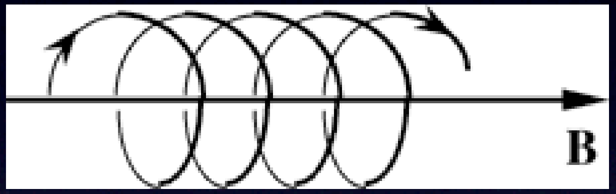




- Three confinement schemes: Gravitational (stars), magnetic (e.g. tokamak), inertial (laser fusion, hydrogen bomb)

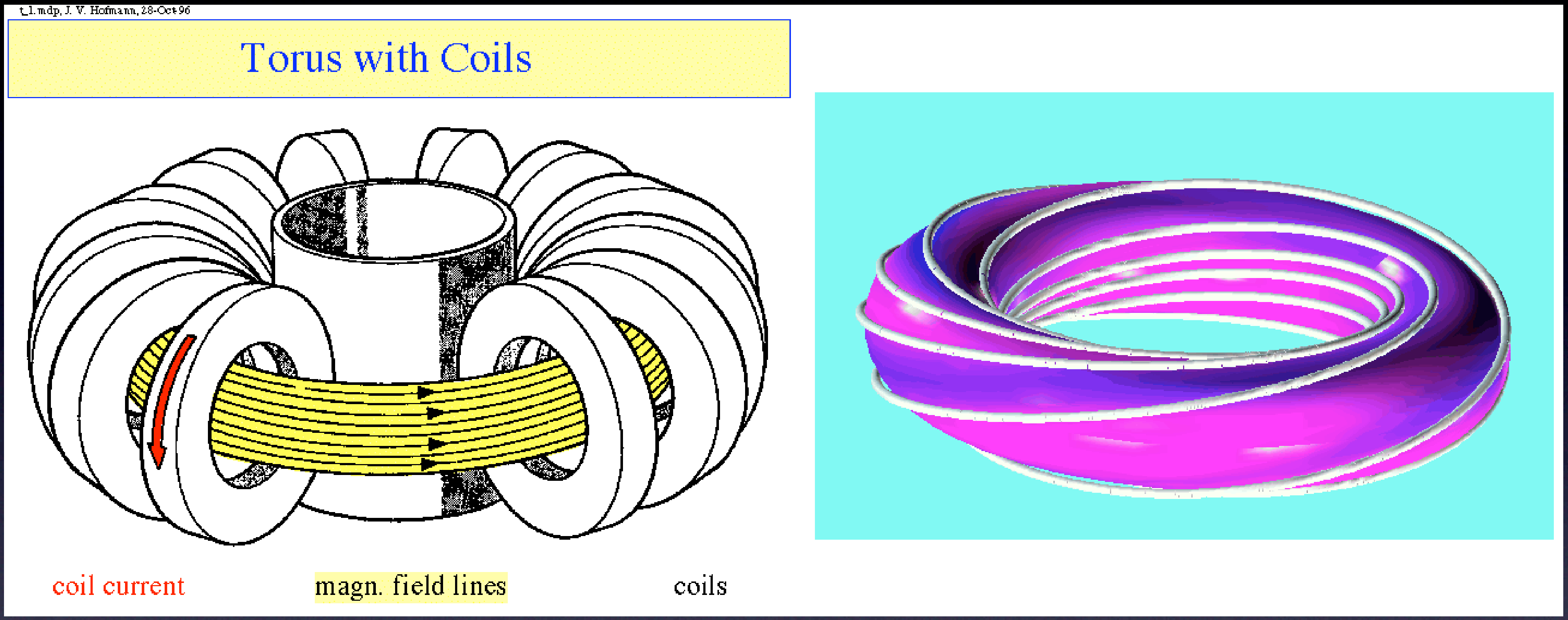
Magnetic confinement of plasma





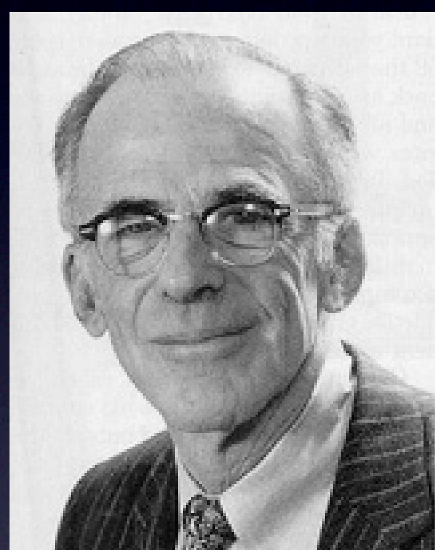
- Astrophysical example of magnetic confinement: prominence in the solar corona (TRACE satellite)
- Charged particles are confined to magnetic field lines (execute helical orbits around them), BUT no confinement along lines

The Tokamak: toroidal magnetic confinement

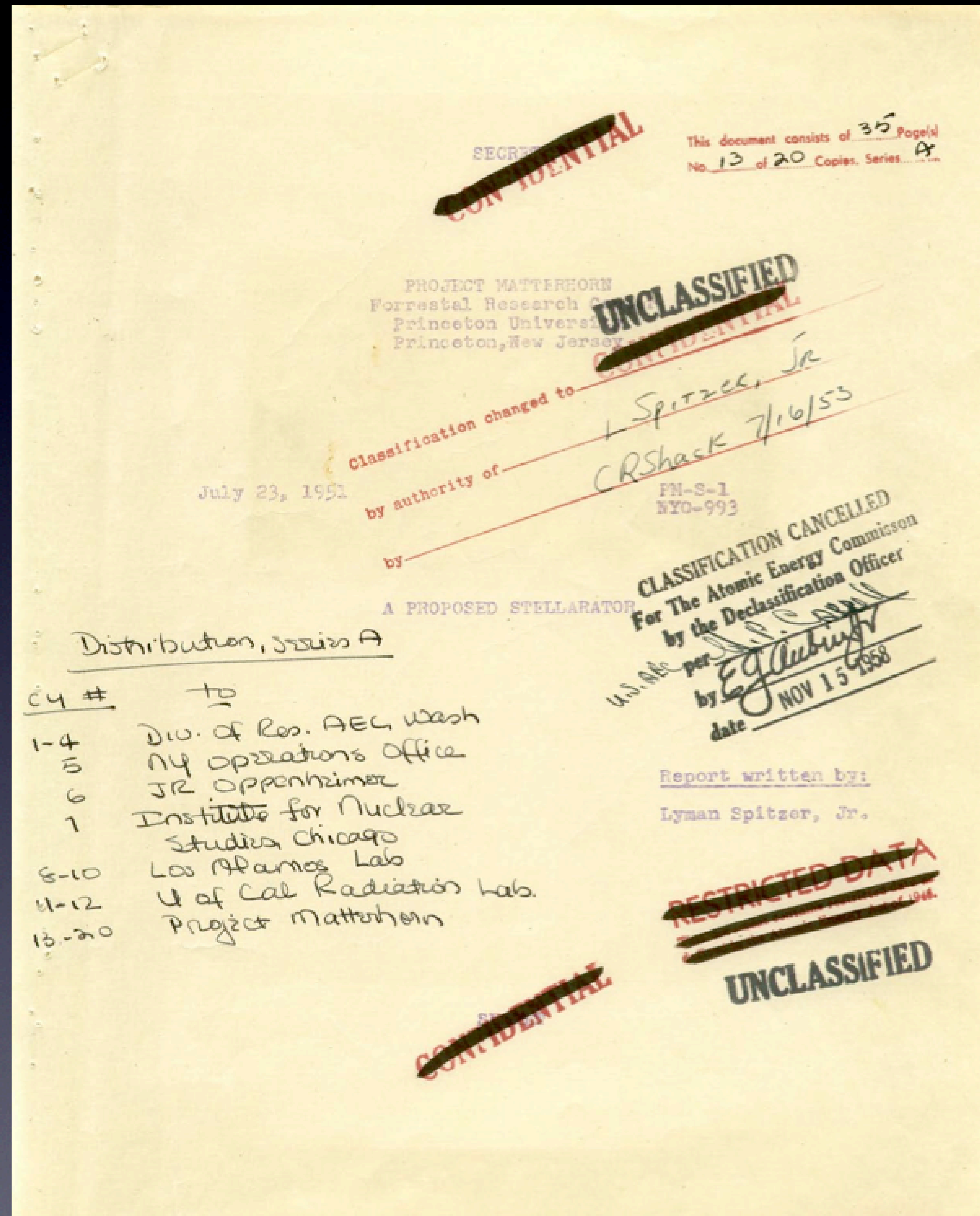


- Toroidal field lines eliminate end losses
- Need helical field to confine charged particles (they drift in curved fields)
- Drive current in the plasma to generate "poloidal field"

A little history: 1951 Optimism



Lyman Spitzer.



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Spitzer's fusion reactor: the stellarator

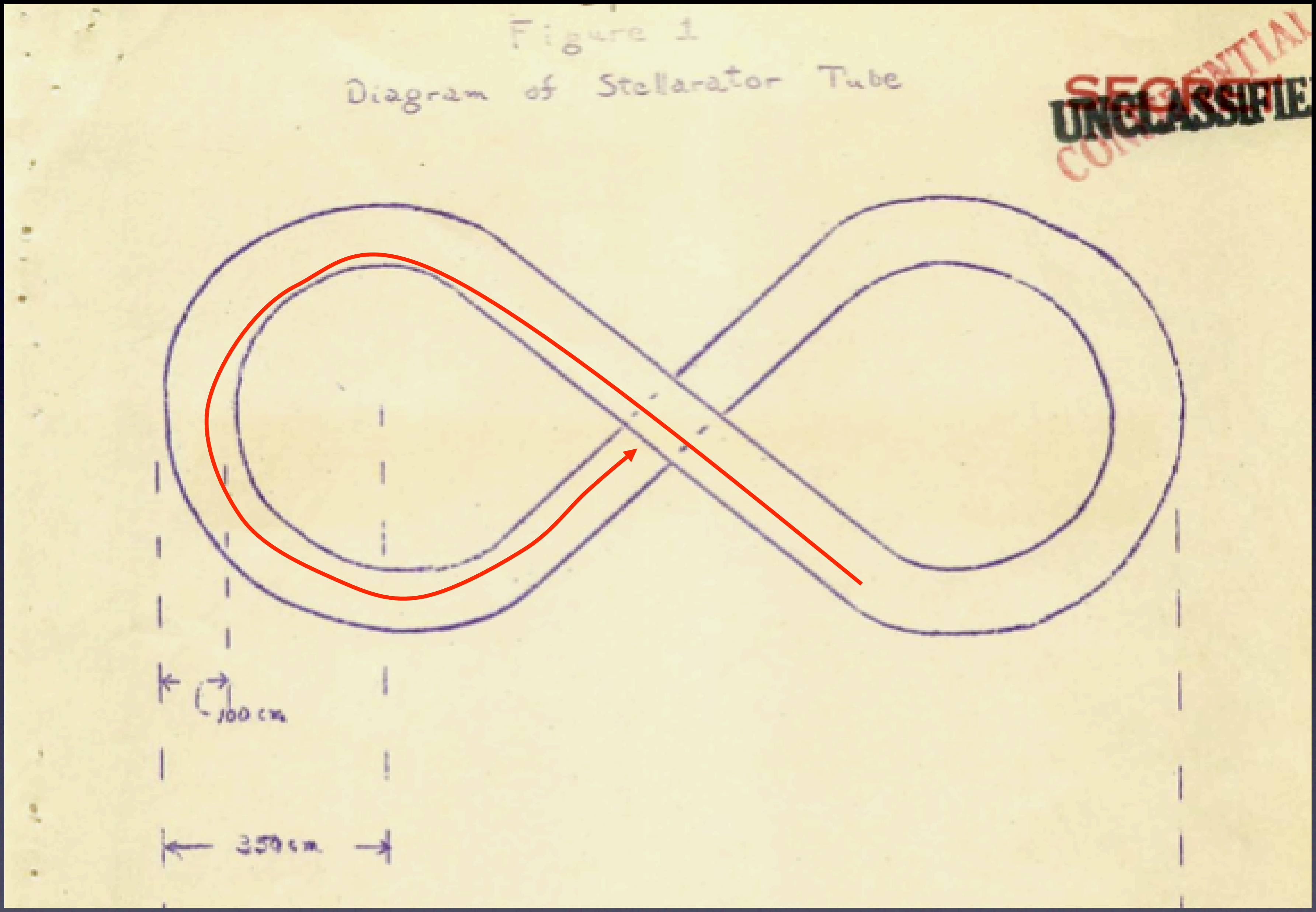
B ~ 50KG.

T> 10keV
n ~ 10^{14}cm

Minor radius
50cm.

Tube length
40-50m.

DT fusion
Power. 150MW

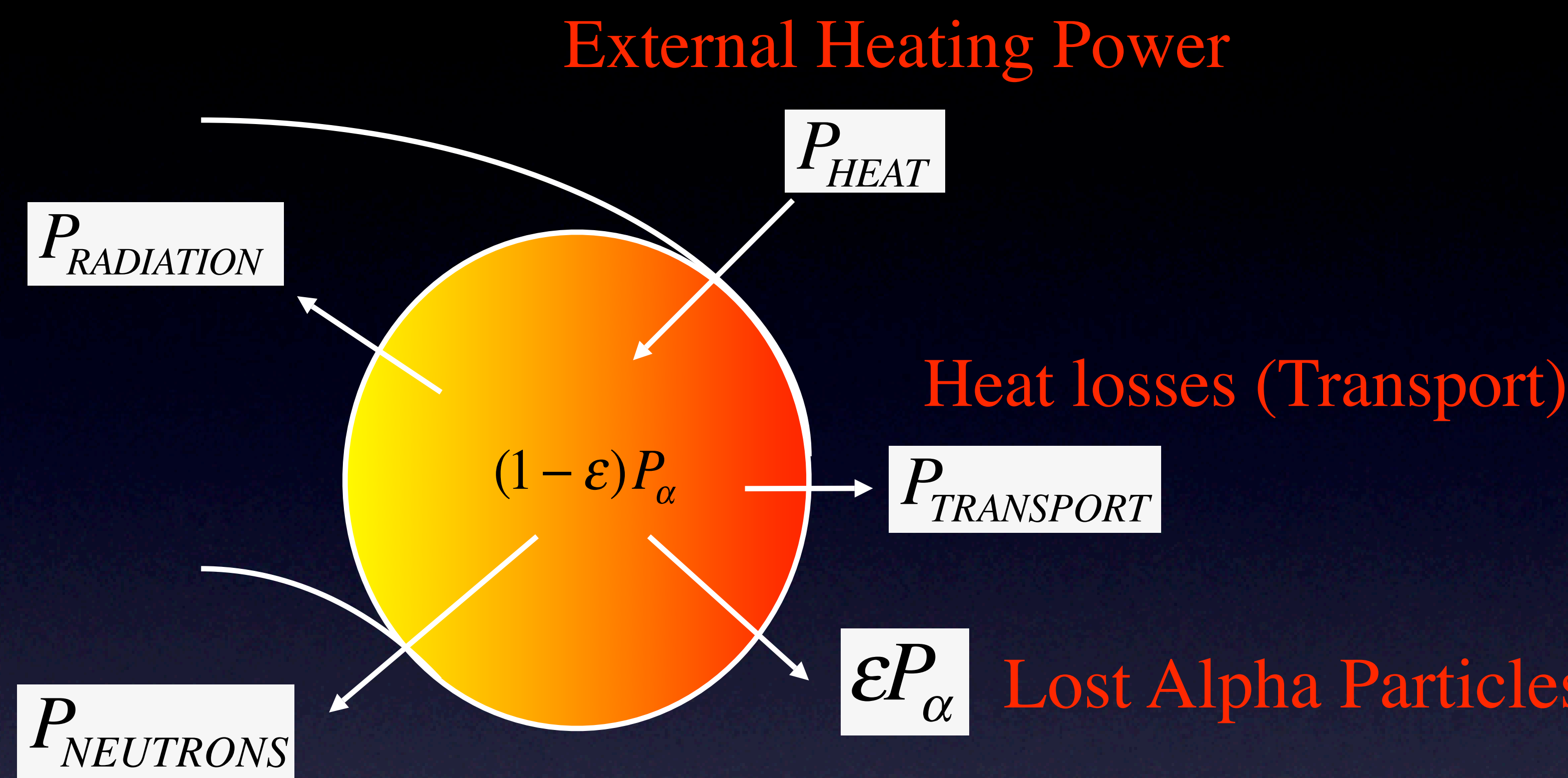


Why didn't it work? Transport (confinement is not perfect)

Fusion Energy Balance in a Magnetic Bottle

$$D + T \rightarrow He^4 + n$$

3.5MeV 14MeV



$$P_{FUSION} = P_{NEUTRONS} + P_\alpha = 5P_\alpha$$

- External heating + Alpha heating has to balance losses due to transport and radiation
- If losses are too big, heating power can be bigger than fusion power in order to maintain temperature

A few definitions

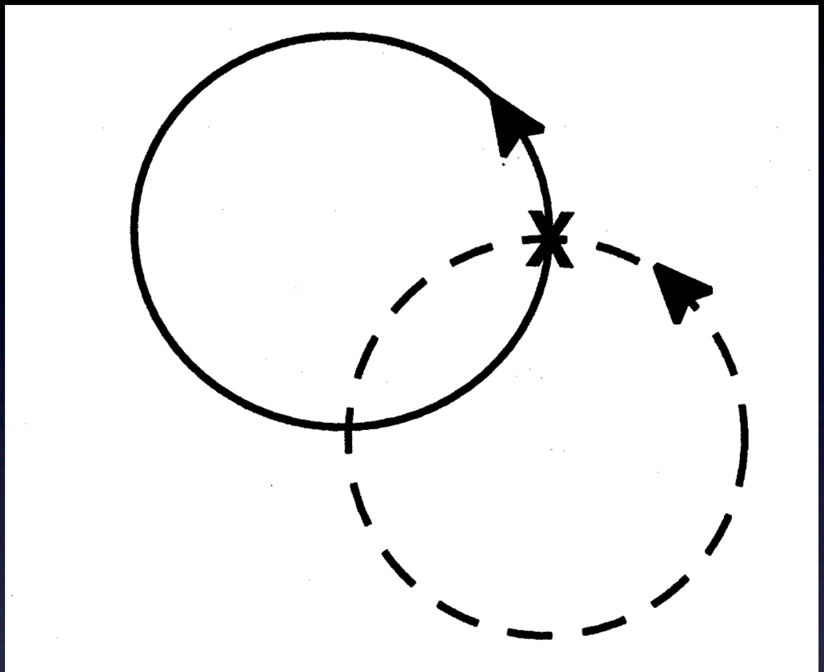
$$P_{TRANSPORT} = \frac{nTV}{\tau_E}$$

Energy Confinement Time.

$$Q = \frac{P_{FUSION}}{P_{HEAT}} = \frac{P_{NEUTRONS} + P_{\alpha}}{P_{HEAT}} = \frac{5P_{\alpha}}{P_{HEAT}}$$

- Q=1 is breakeven, Q=5 is 50% alpha heated, and Q=infinity is ignition (no external heat required)
- World record Q's: TFTR Q=0.27, JET Q=0.61
- Transport determines confinement time, which in turn sets required heating power and therefore Q

Classical (collisional) transport is predicted to be very small



- Charged particles collide with one another, causing a change in direction and a "step" across the magnetic field
- Many collisions: random-walk diffusion
- But collisions are rare in a hot plasma (and step size is small), Spitzer's reactor should have been good enough for ignition!

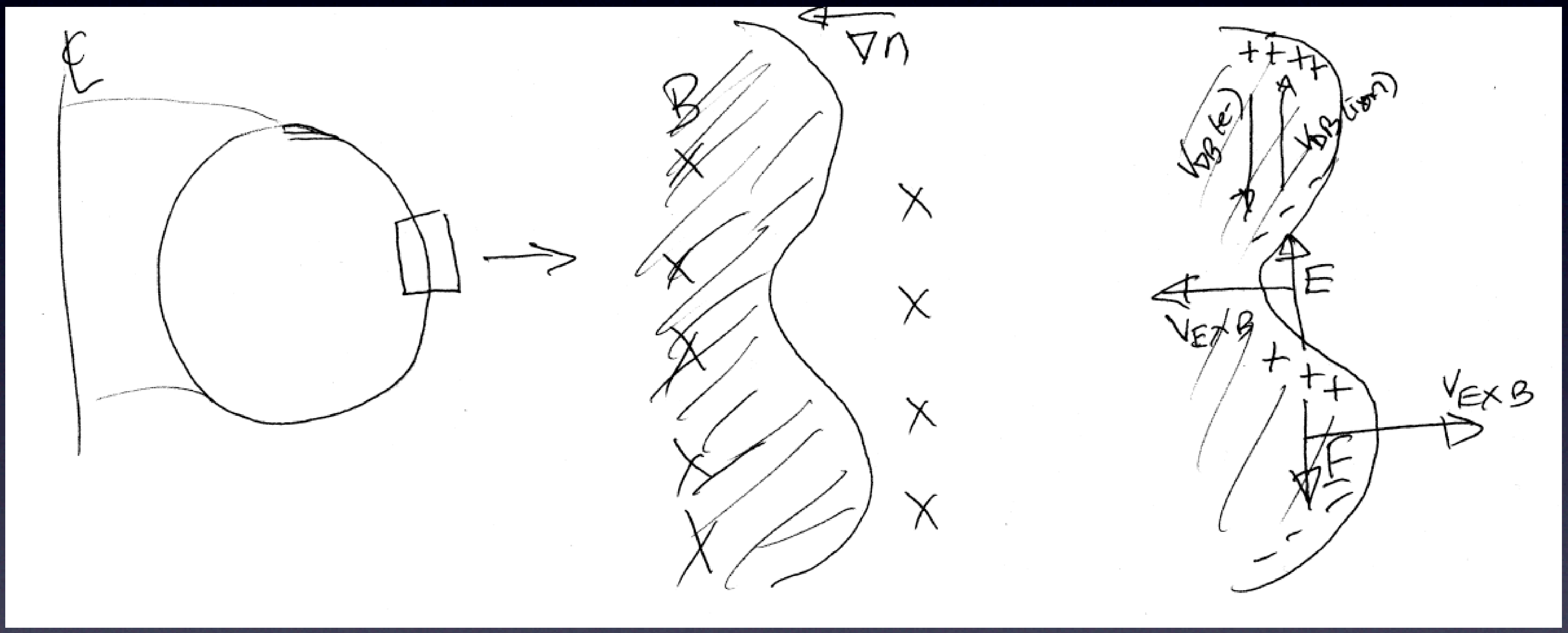
Transport by turbulence can be significantly bigger than classical transport

- Not quite right: Particles "scatter" off of electric fields associated with collective oscillations in the plasma (much longer range than classical collisions)
- Really: ExB motion driven by fluctuations causes transport (for electrostatic modes)
- What causes fluctuations? Unstable plasma waves driven by free energy sources in the plasma

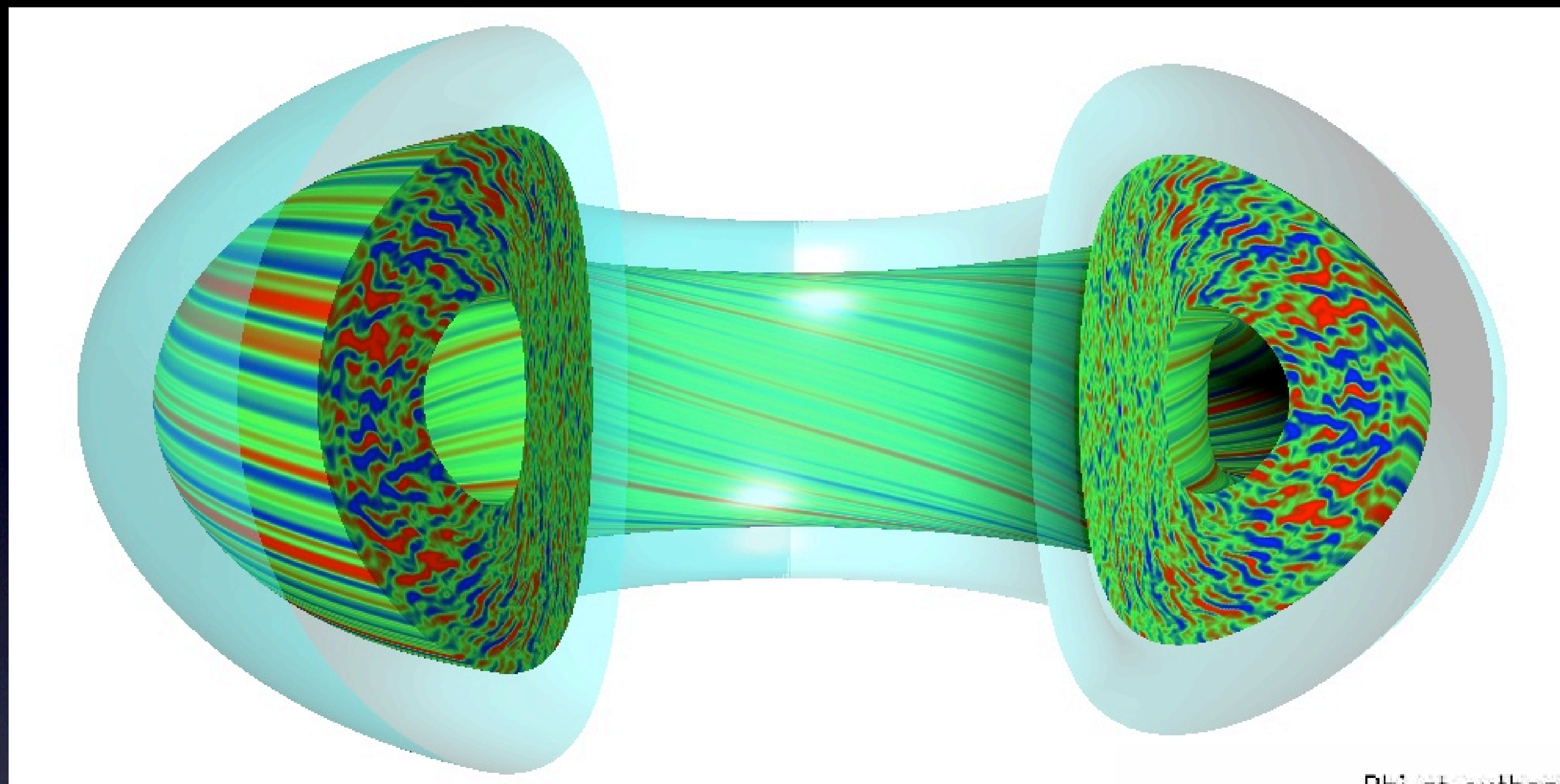
Gradient-driven instabilities

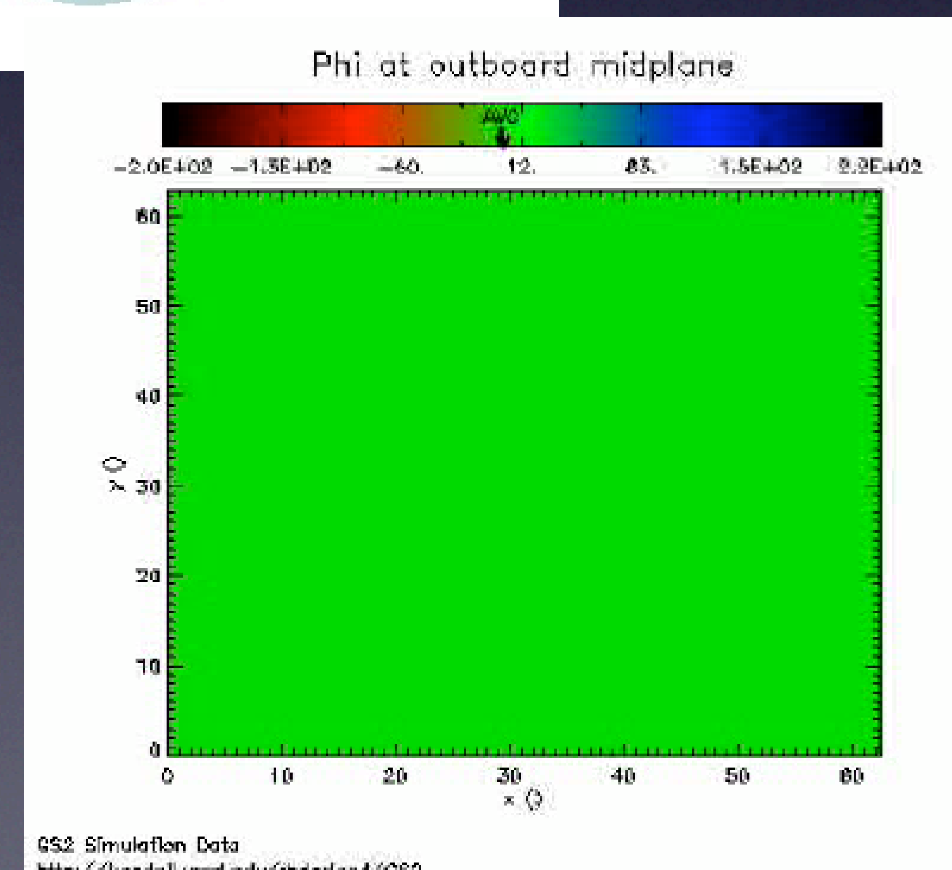
- Global thermodynamic equilibrium would require the plasma to have a flat temperature and density profile (same T as wall) -- any departure from this represents a source of free energy
- Motions in the plasma which attempt to flatten temperature profile (e.g. mixing) can tap this free energy source (can be unstable)

Simple physical picture of Gradient/ Curvature driven instability



Massively parallel simulations of tokamak turbulence



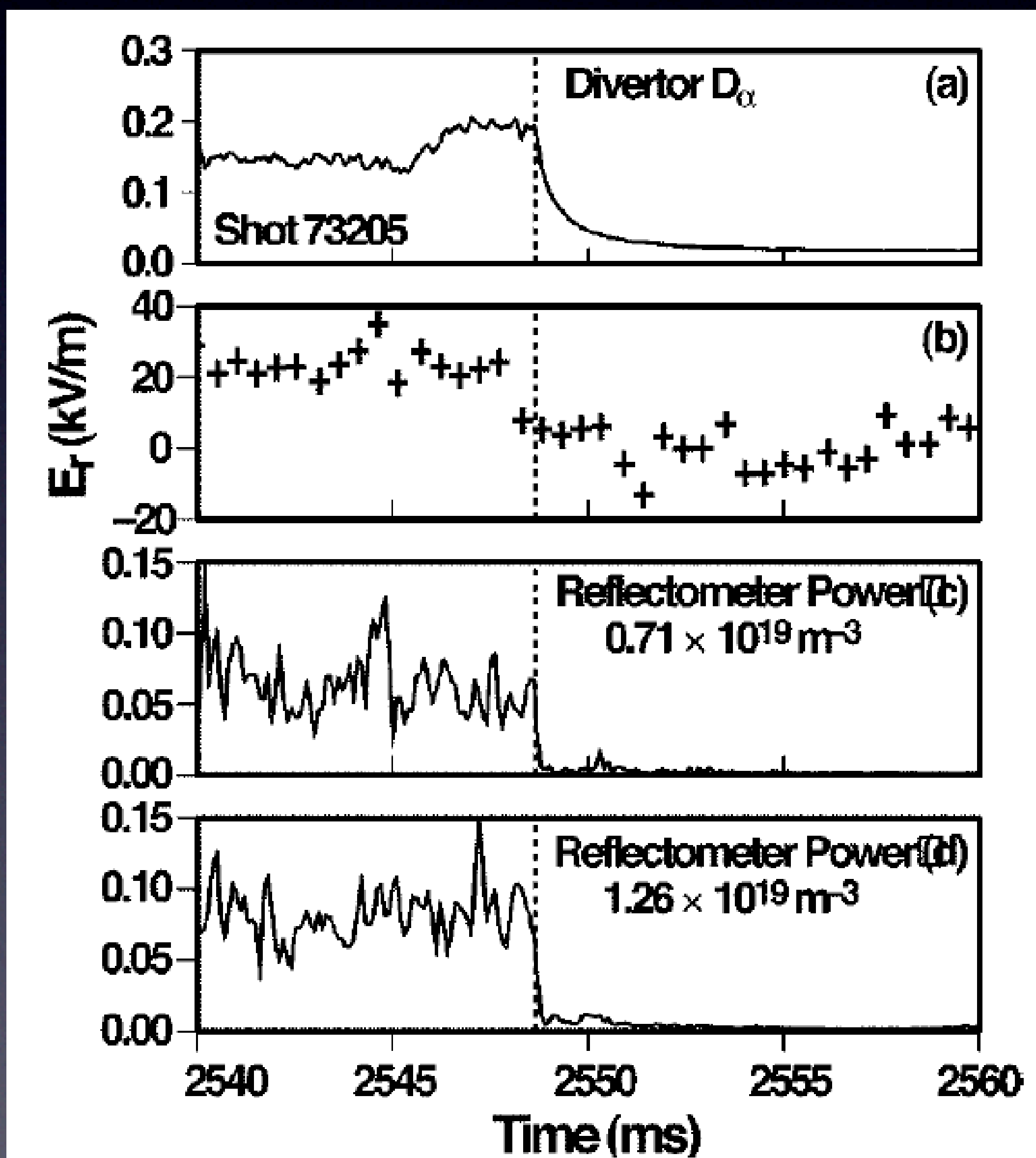


- Ion Temperature Gradient driven turbulence (ITG)
- Convective cells carry heat and particles from core to edge much faster than collisions

Turbulent diffusion estimates

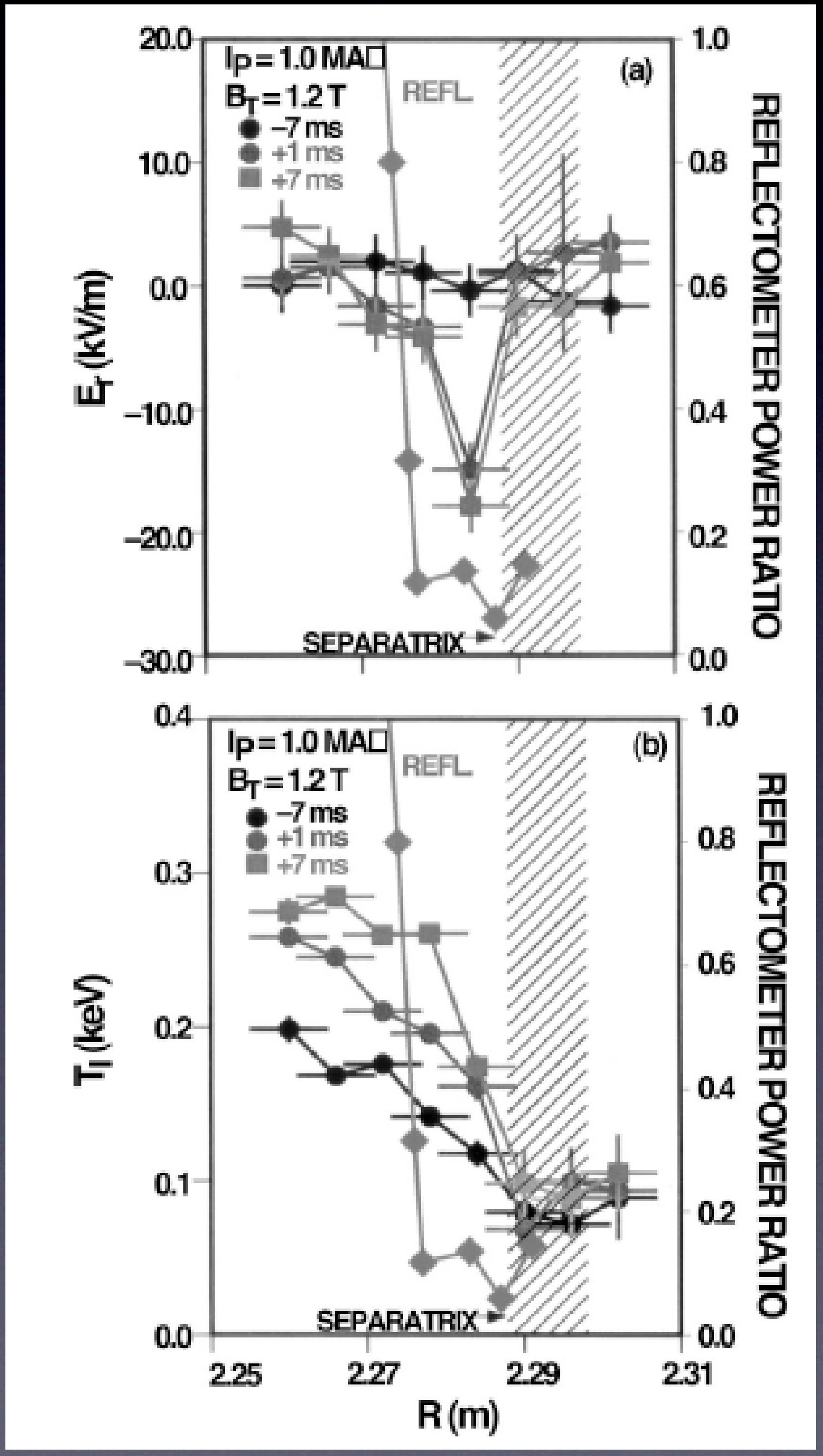
- Mixing length estimate: step size is correlation length (~size of eddy), time step is correlation time (or "eddy turnover time")
- Spatial step ~10 ρ_i, time step ~$1/\omega$ (linear mode frequency) (<< collision time scale)
- Leads to diffusion coefficent a couple of orders of magnitude (or more!) bigger than classical diffusion
- Confinement gets worse with increasing heating power ("L-mode"), as the step size increases

Turbulence and transport suppression in H-mode



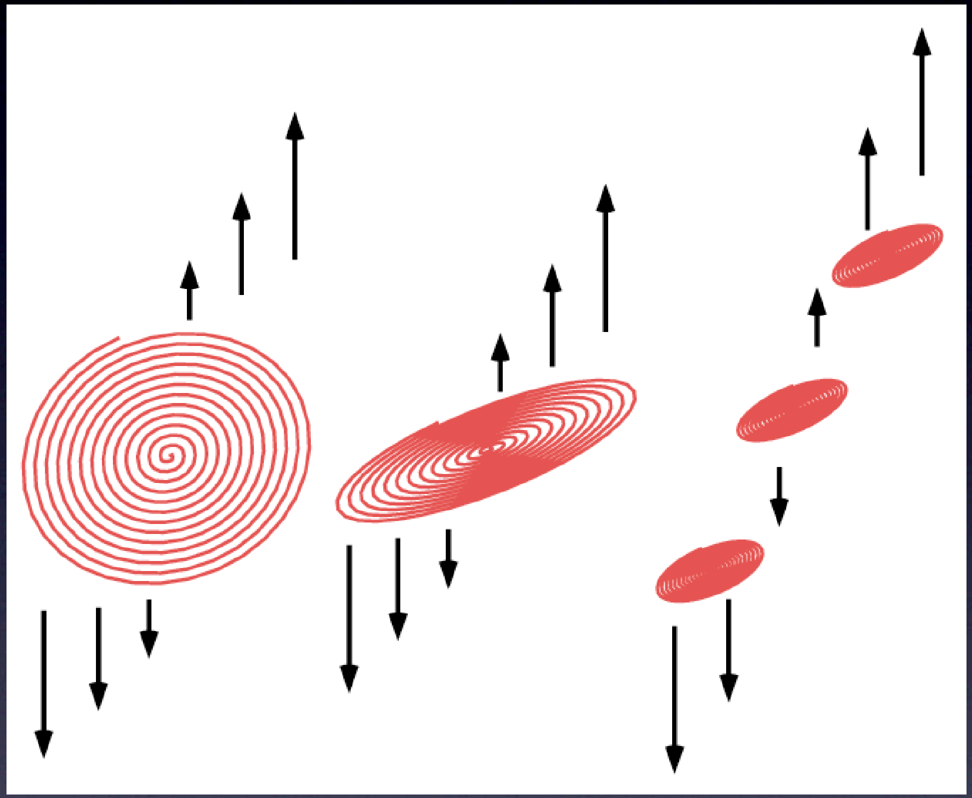
- Spontaneous confinement transport improvement with increased heating power
- Fluctuations in edge reduced, recycling reduced
- Edge transport barrier (and "pedestal") observed
- Sheared flow (radial E field) develops simultaneously

Sheared flow at edge coincident with turbulence reduction



- Shear layer forms at H-mode transition
- Turbulence suppressed in the region of the shear layer
- Transport significantly reduced, "pedestal" forms

Success in theoretical understanding: suppression of turbulence by sheared flow in barrier

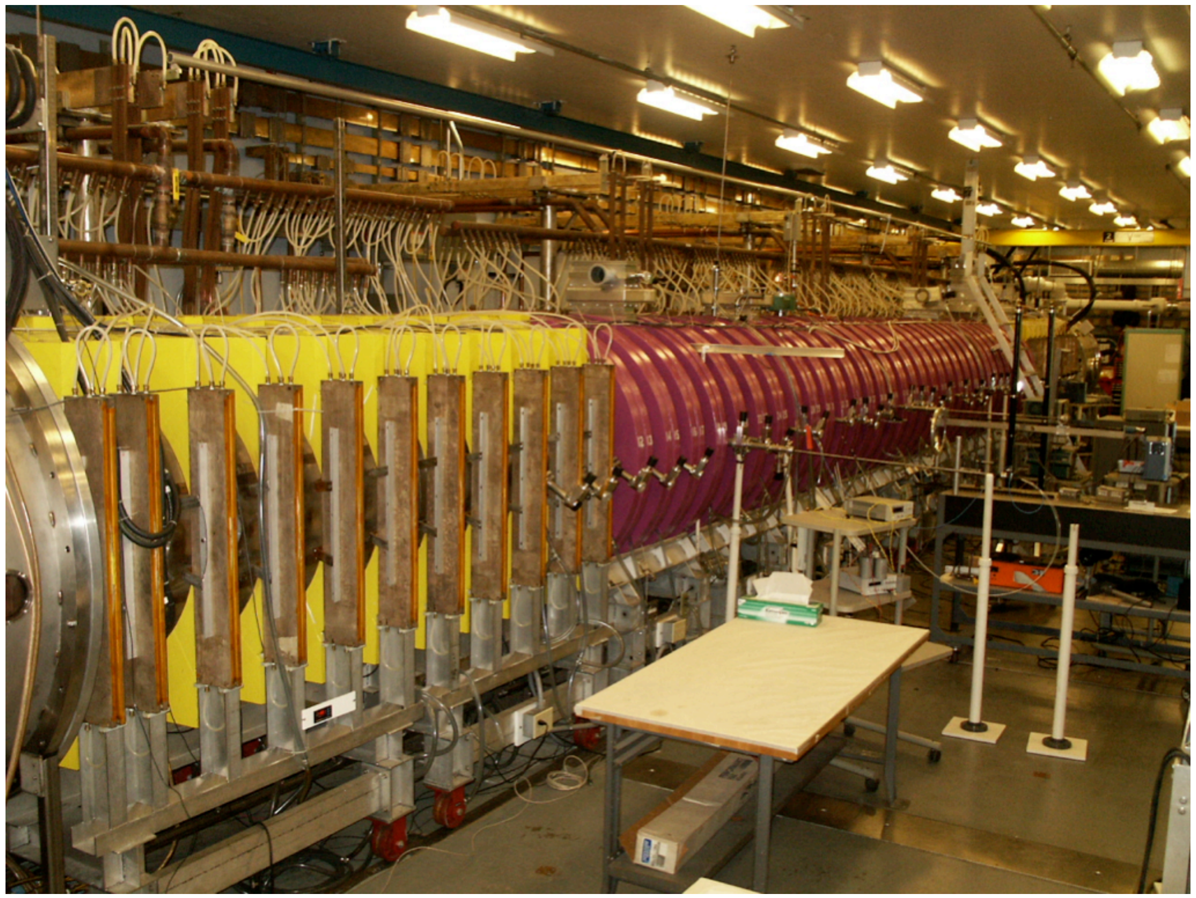


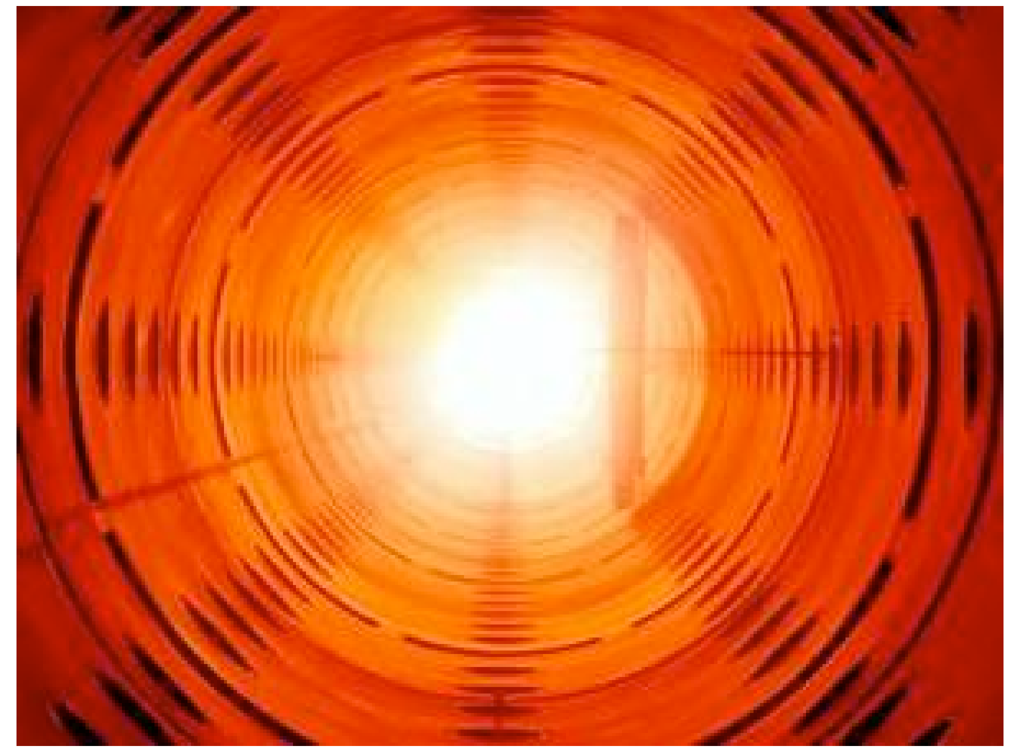
- Sheared flow rips eddies apart, smaller eddies means shorter transport steps

Code: GYRO

Authors: Jeff Candy and Ron Waltz

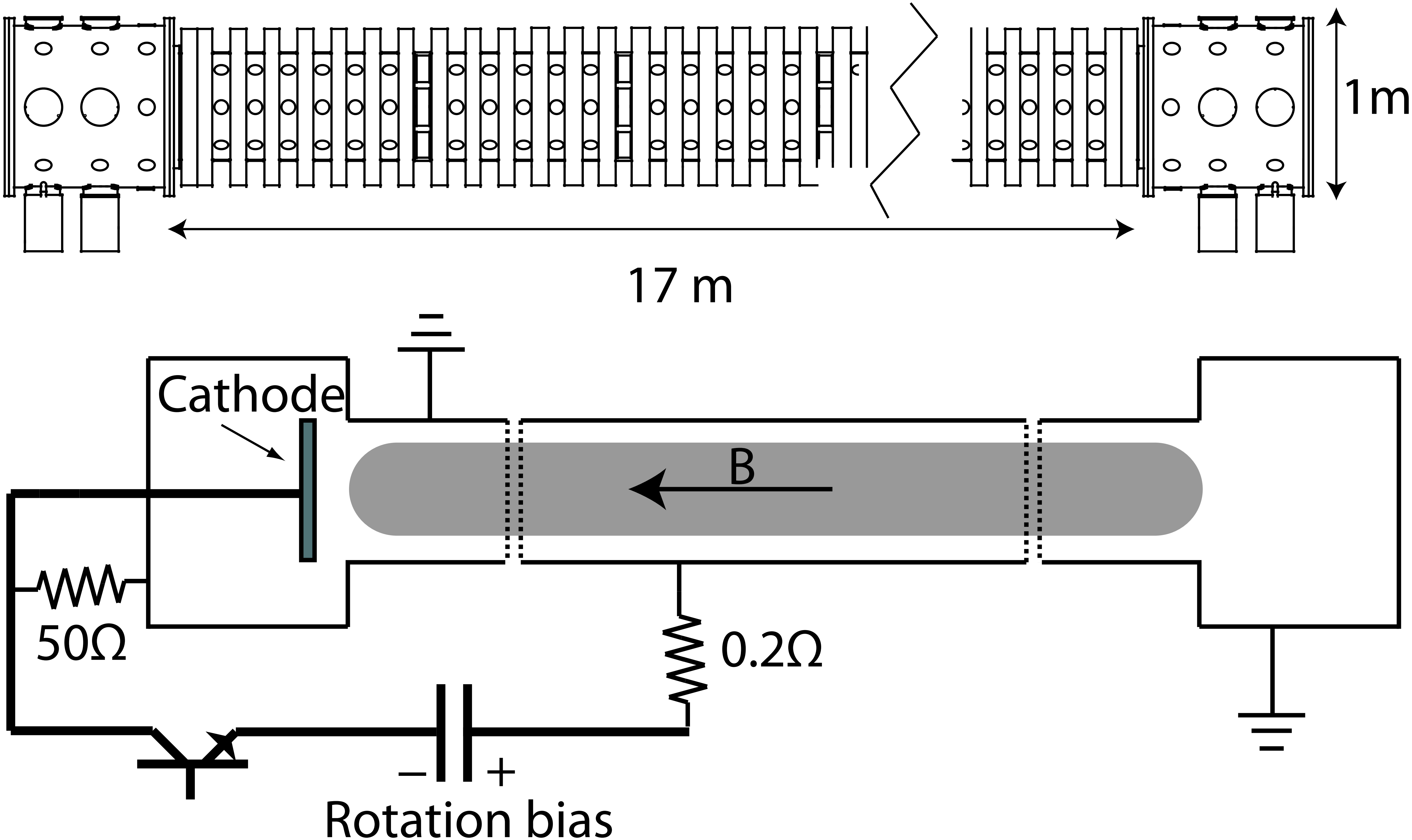
Shear Suppression on The Large Plasma Device (LAPD) at UCLA



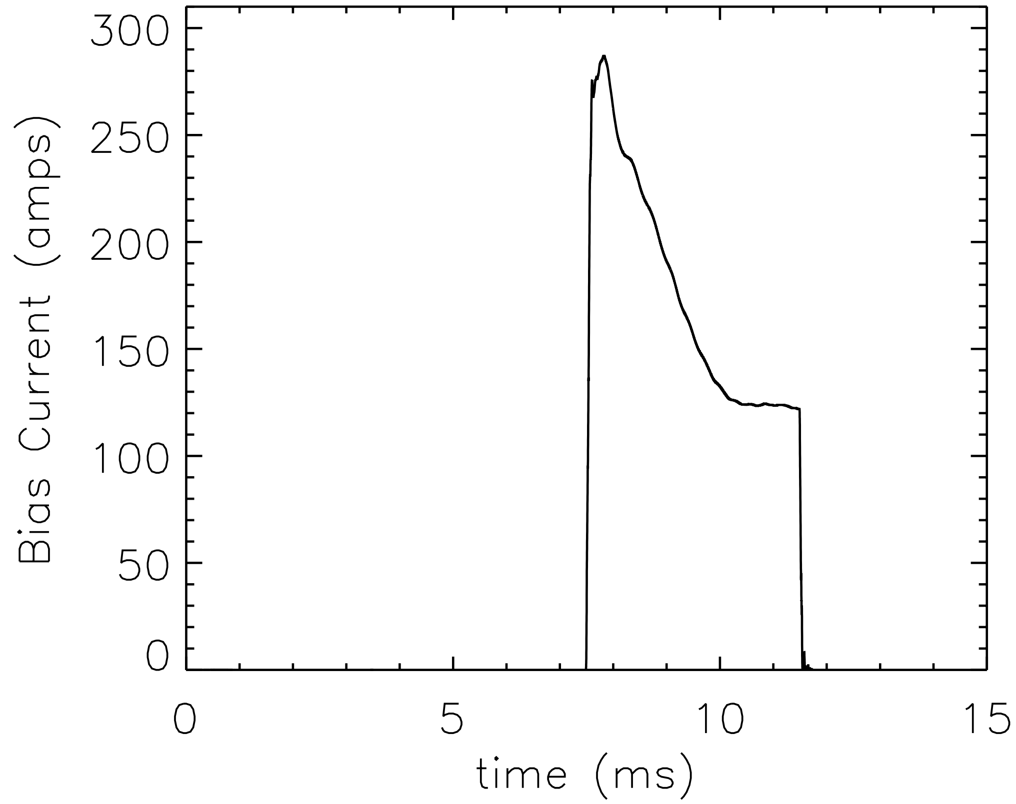


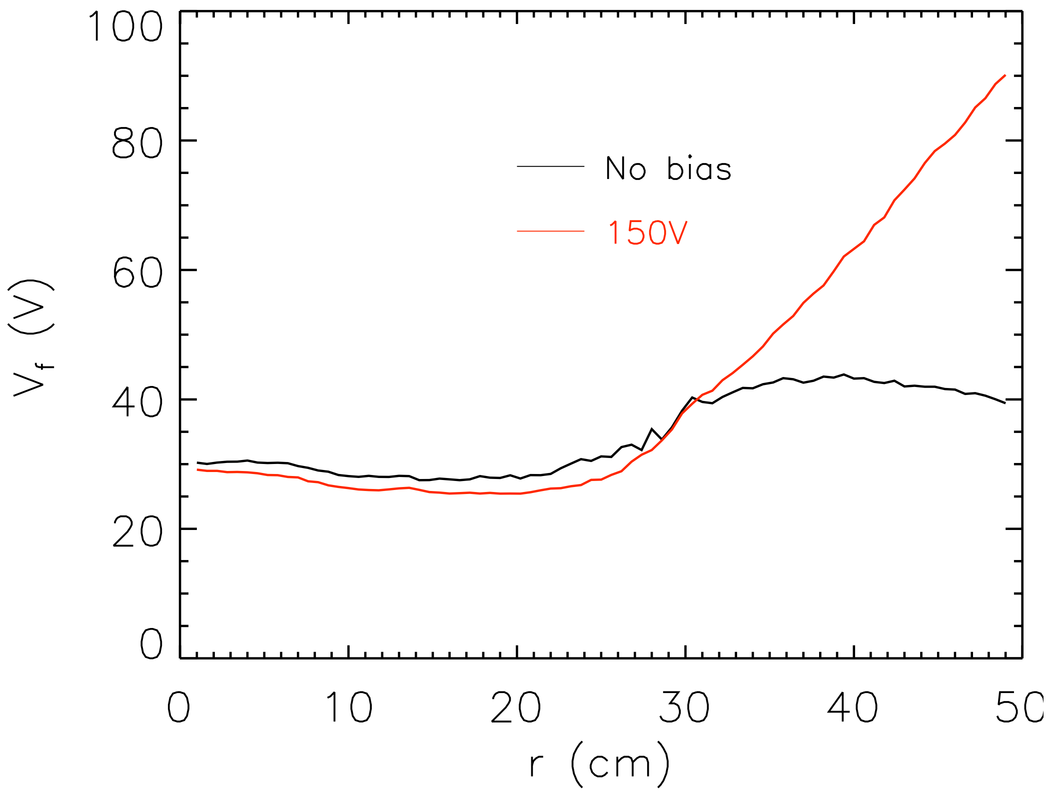
- 17m long, 1m ID cylindrical chamber (plasma < 60cm), Barium Oxide coated nickel cathode source (pulsed, 10 ms, 1 Hz rep rate)
- Typical parameters: $n_e \sim 10^{12}$ cm^{-3}, $T_e \sim$ 10eV, $T_i \sim$ 1eV, 400G < B < 2kG
- Working gases: He, Ne, Ar, H
- US DOE/NSF sponsored user facility: http://plasma.physics.ucla.edu/bapsf

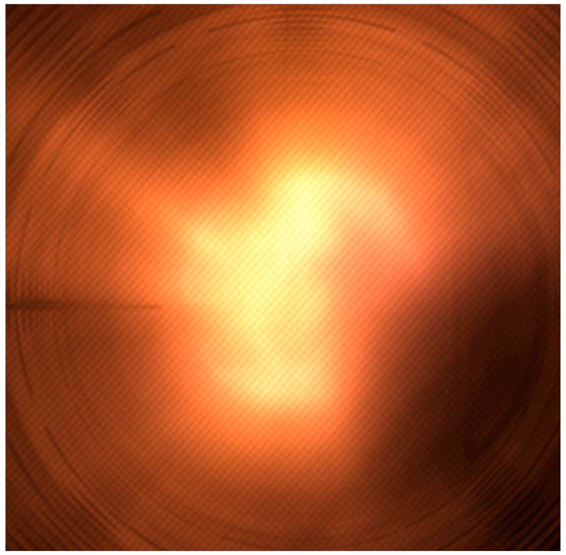
Driven shear flow with biased rotation in LAPD



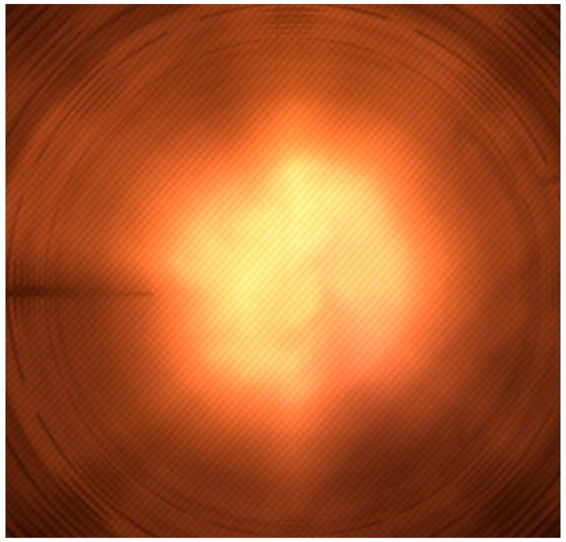
Biasing creates electric fields in the edge and "cleans up" edge in visible images



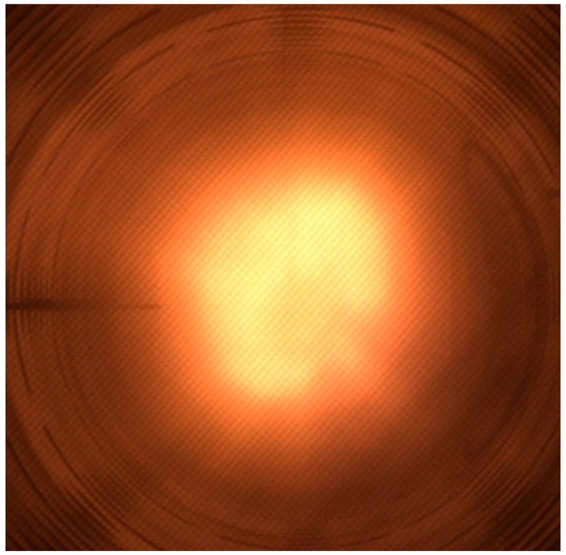




No bias

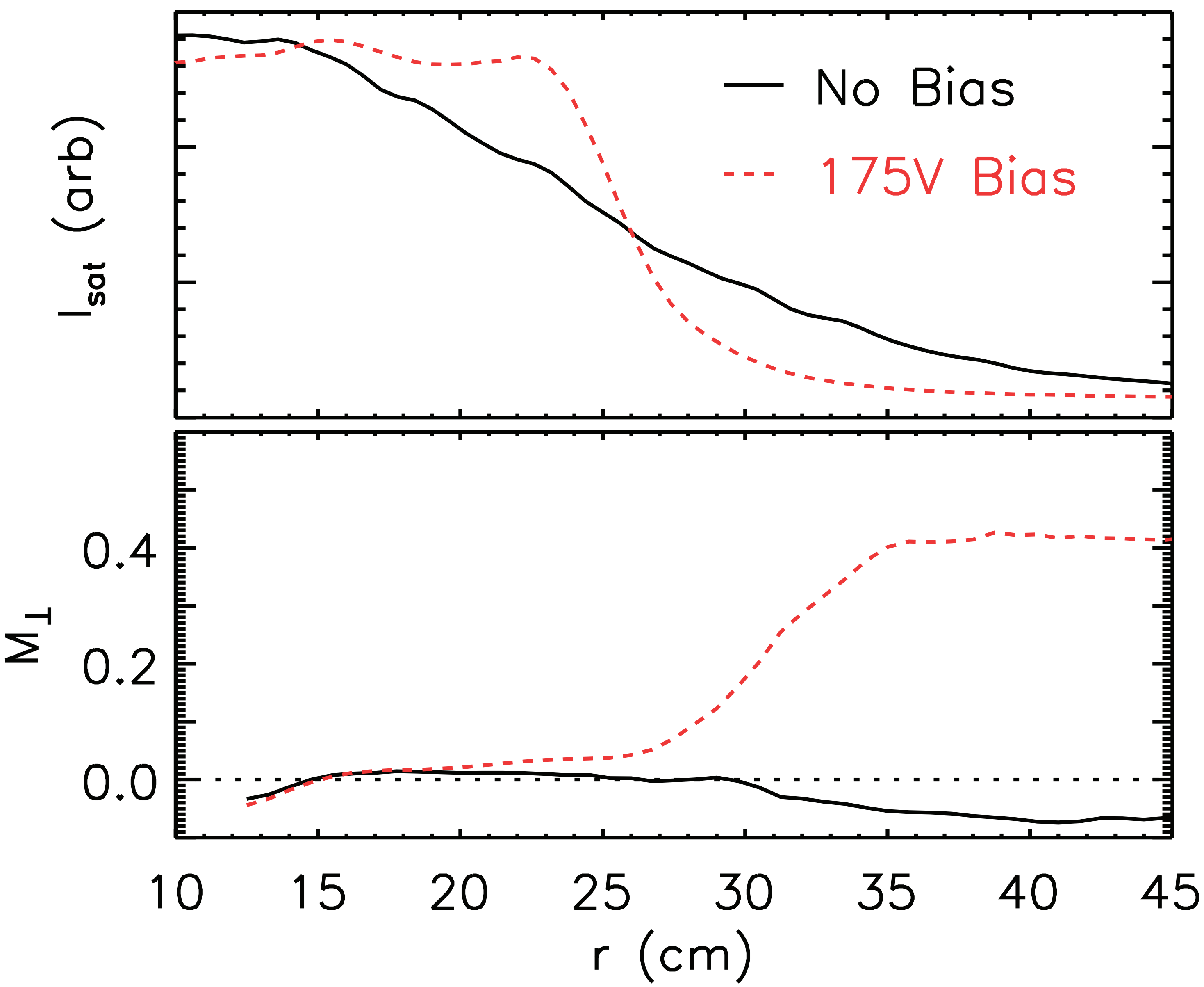


75V

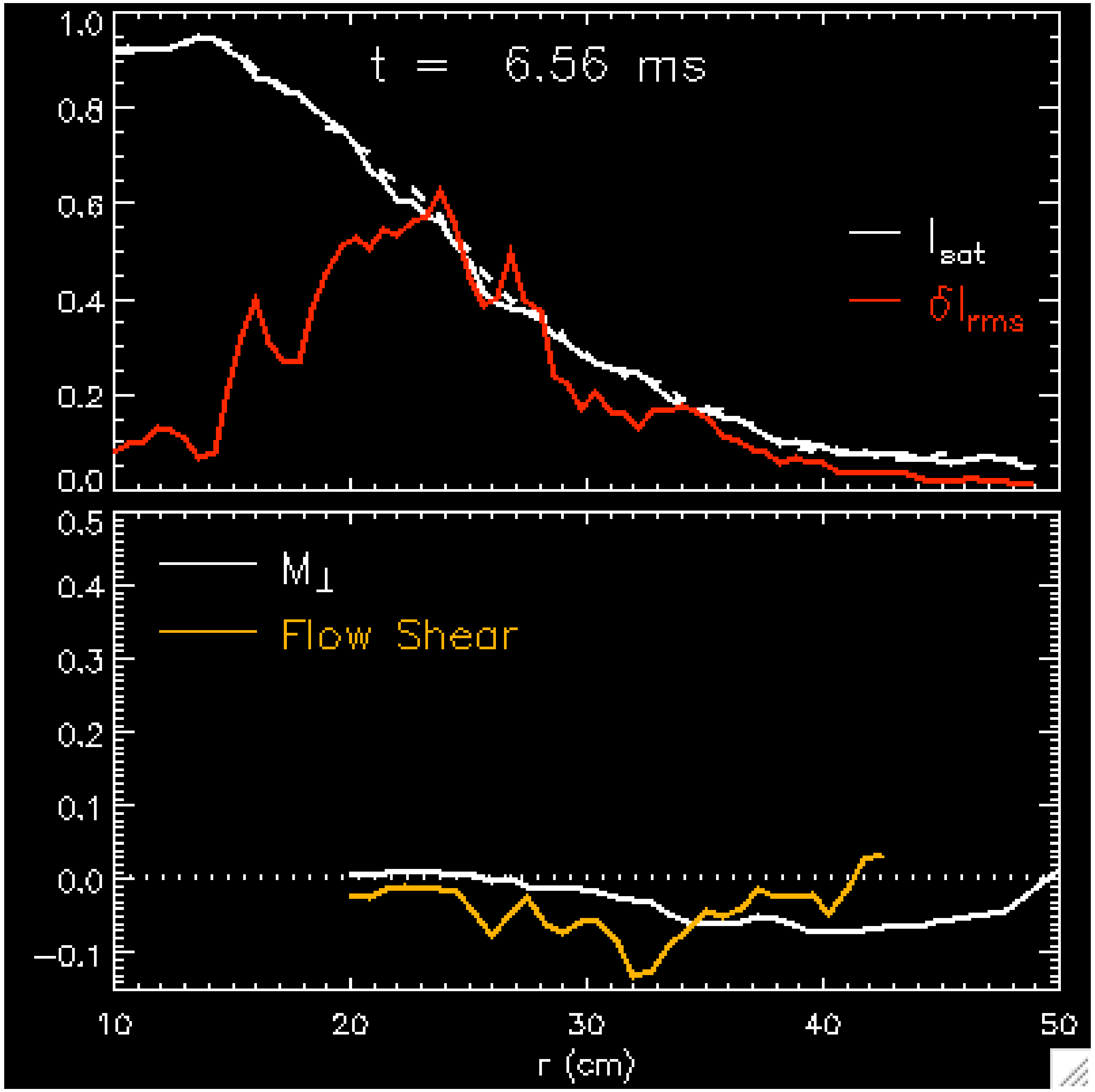


150V

Edge profiles steepen during biased rotation

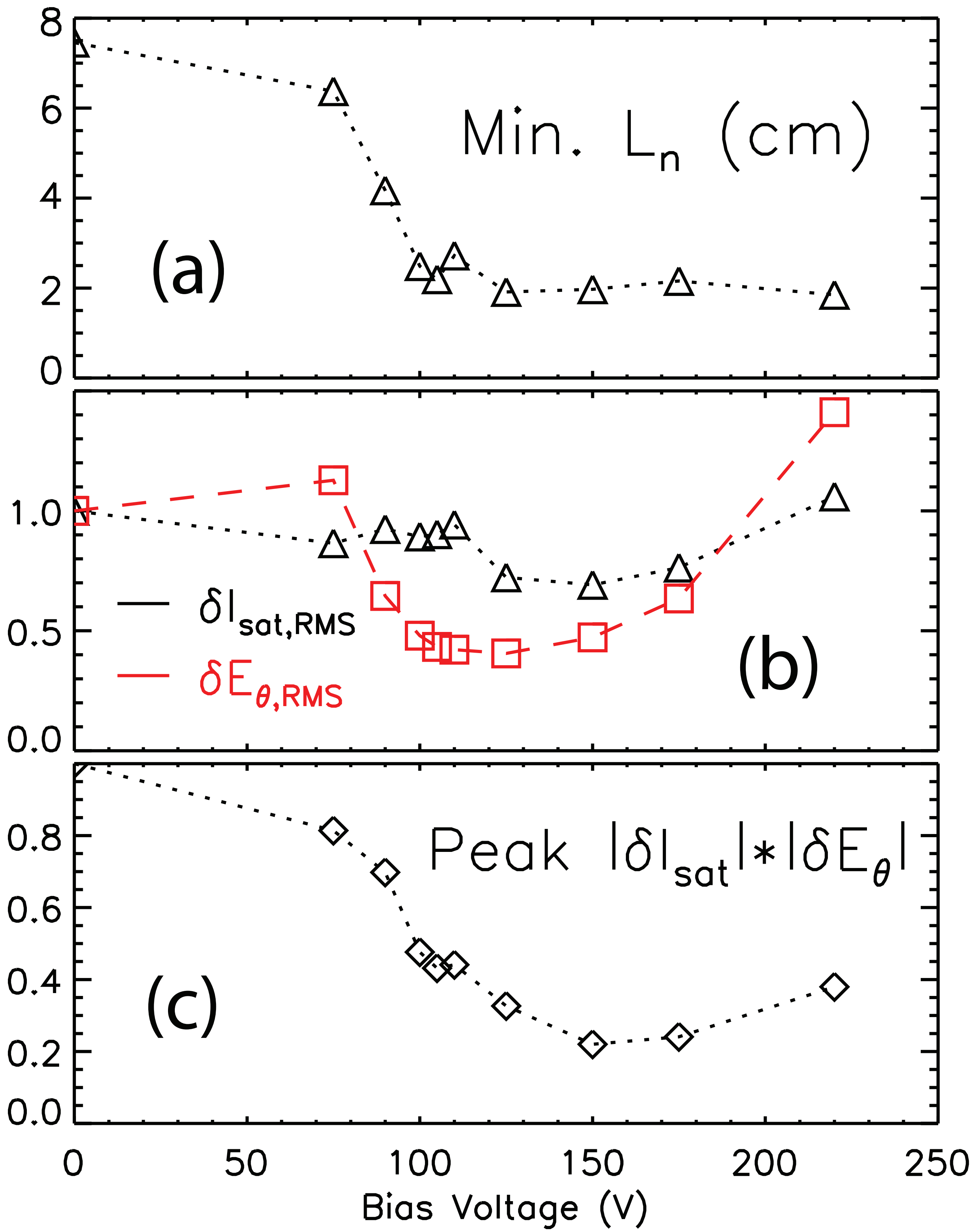


- Triple Langmuir probe measured density, flow measurements using 6 face Gundestrup (Mach) probe
- Measured flow consistent with ExB (E ~ 100 V/m), observed shearing rate is comparable to ω^* (~20kHz)
- Threshold bias for steepening is observed
- Dynamics: profile change on transport timescale (movie)



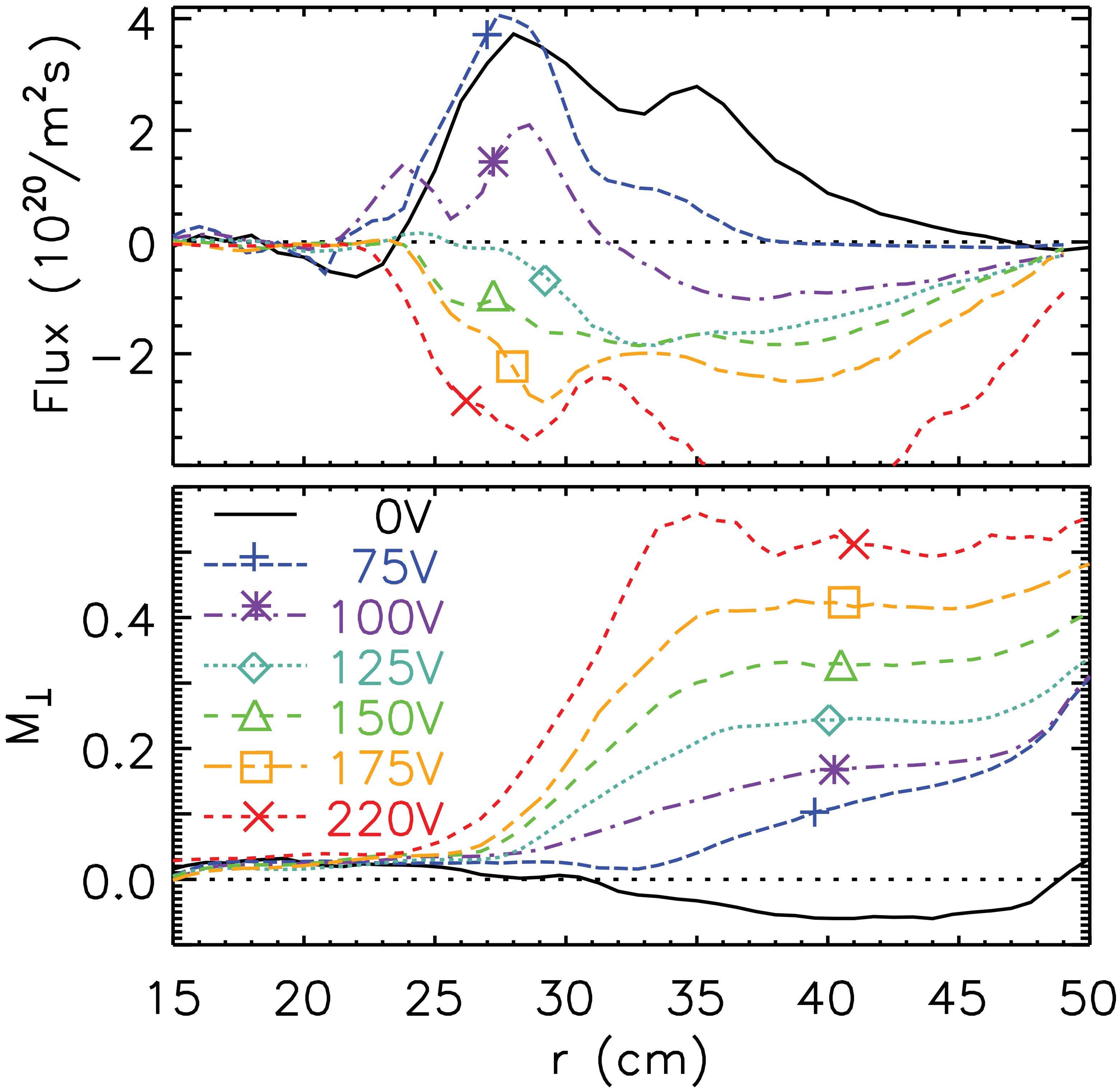
t = 6.56 ms
I_{sat}
δI_{rms}
$M_\perp$
Flow Shear
1.0
0.8
0.6
0.4
0.2
0.0
0.5
0.4
0.3
0.2
0.1
0.0
−0.1
10
20
30
40
50
r (cm)

Gradient scale length, fluctuation amplitude decrease at threshold



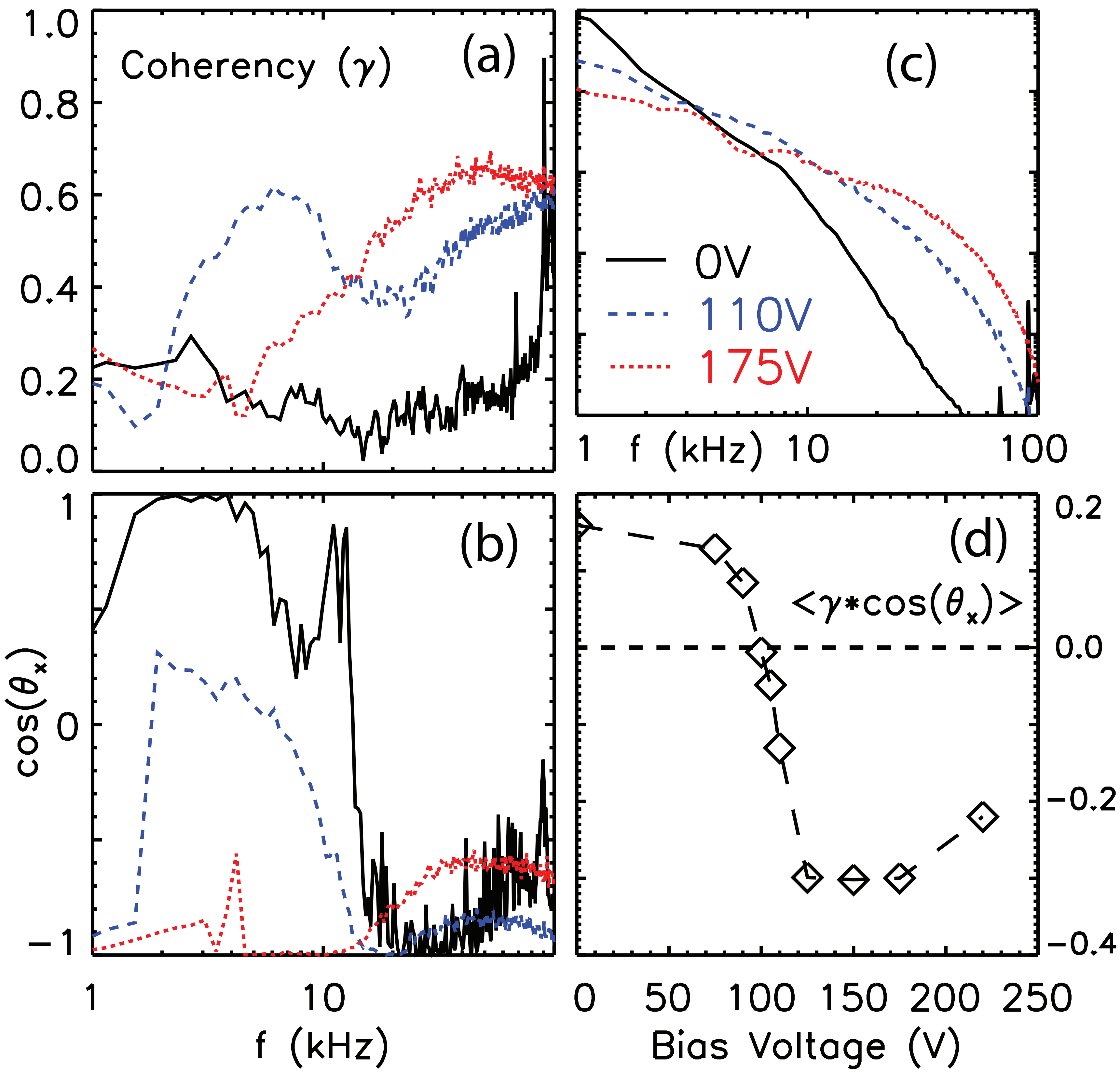
- Past threshold, L_n decreases dramatically, but saturates at ~ 2cm (ρ_s ~ 1cm)
- Peak E_Θ fluctuation amplitude drops at first, but increases again at higher bias
- Product of magnitudes of I_{sat} and E_Θ fluctuations decreases by a factor of 5

Turbulent flux is suppressed and reversed with increasing bias



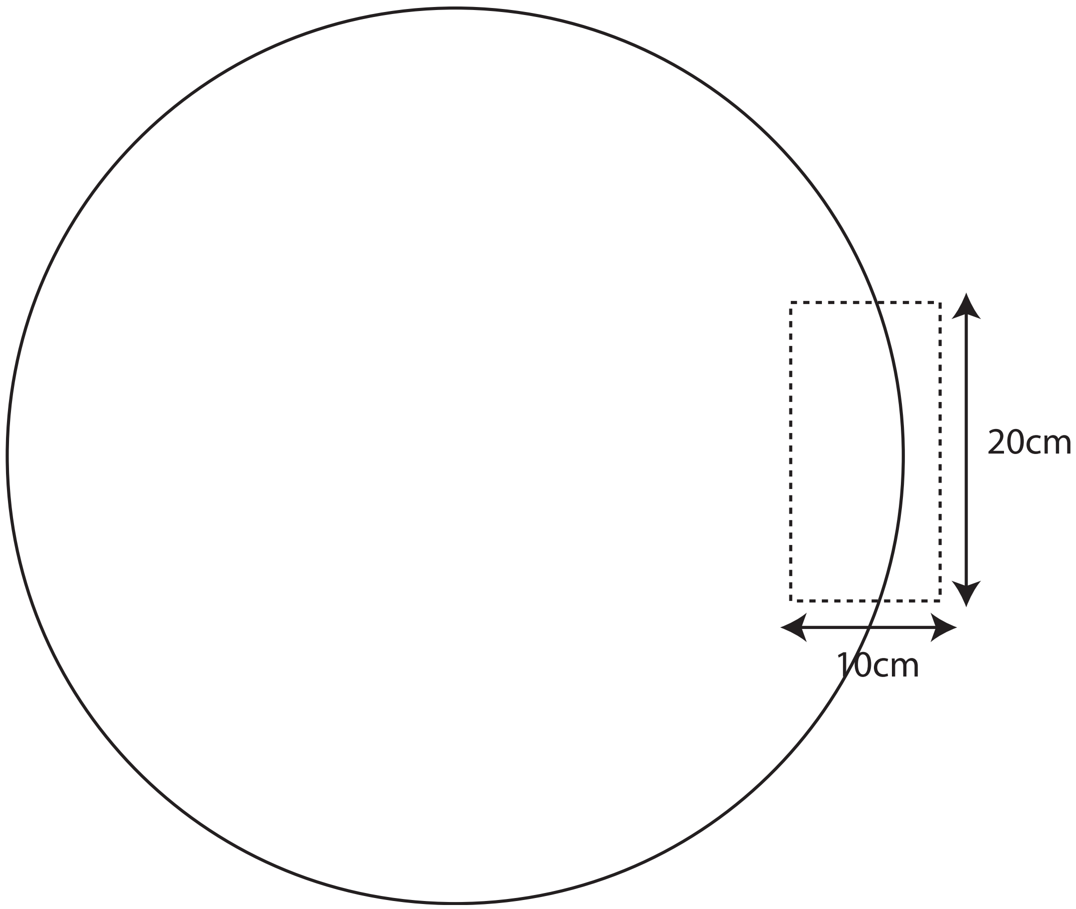
- Suppression of flux is coincident with profile steepening
- Reversal of transport flux in shear flows theoretically predicted [e.g. Terry] observed in other biased experiments [e.g Shats, Boedo]

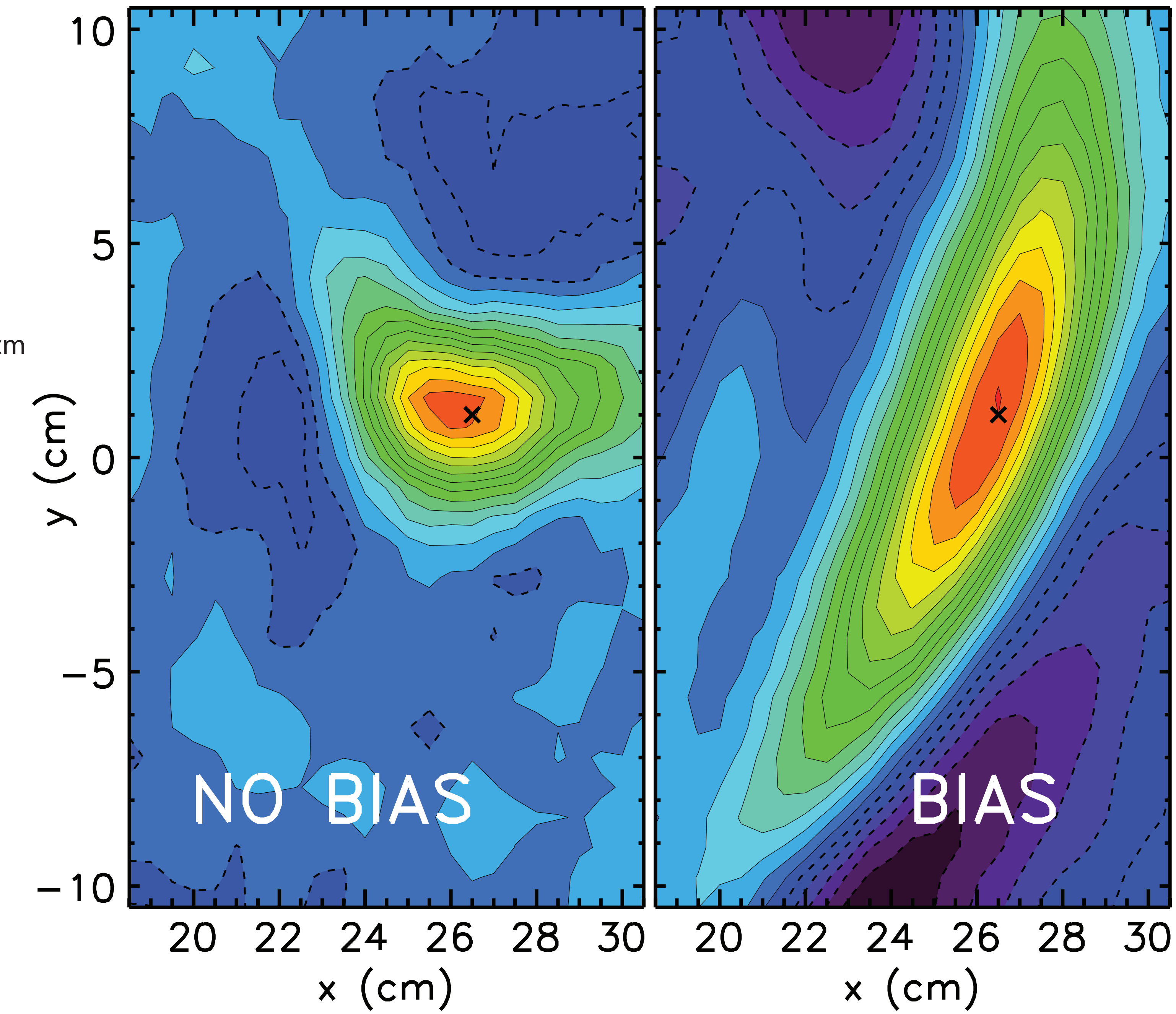
Cross phase changes dramatically during biased rotation



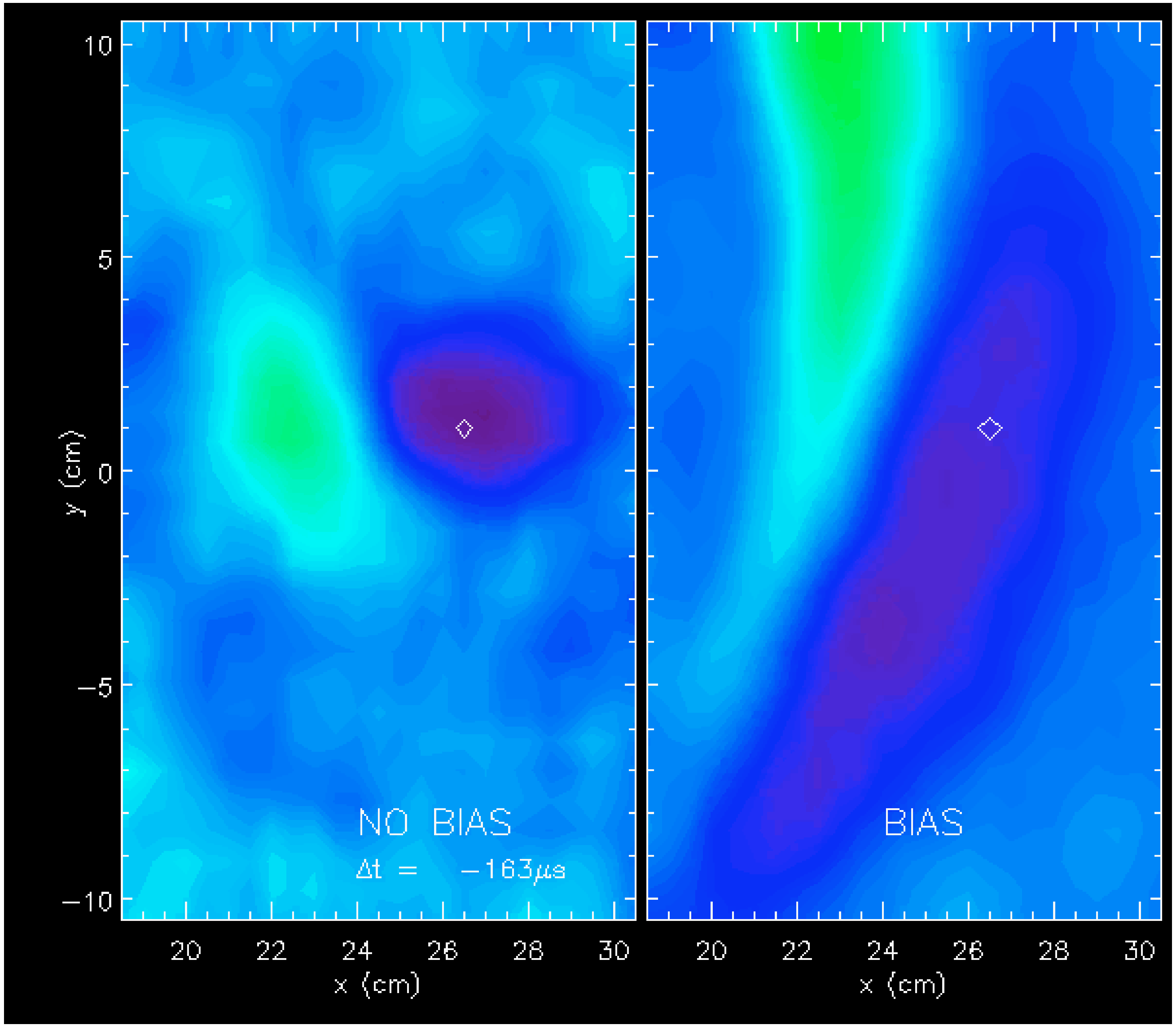
- FFT spectrum: Low f reduction, doppler shift
- Coherency increases with bias
- Cross phase reduced then reversed

2D correlation functions sheared during biased rotation





- Correlation function sheared, with significant azimuthal correlation
- Radial correlation length is reduced, but only slightly

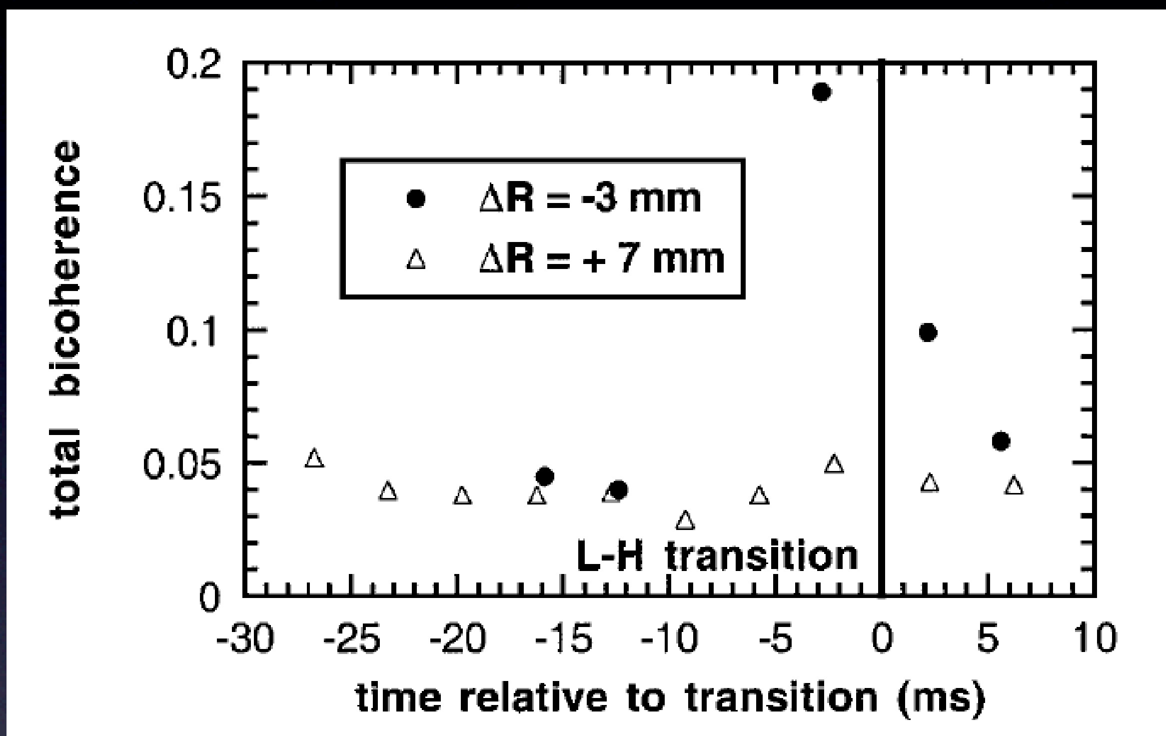


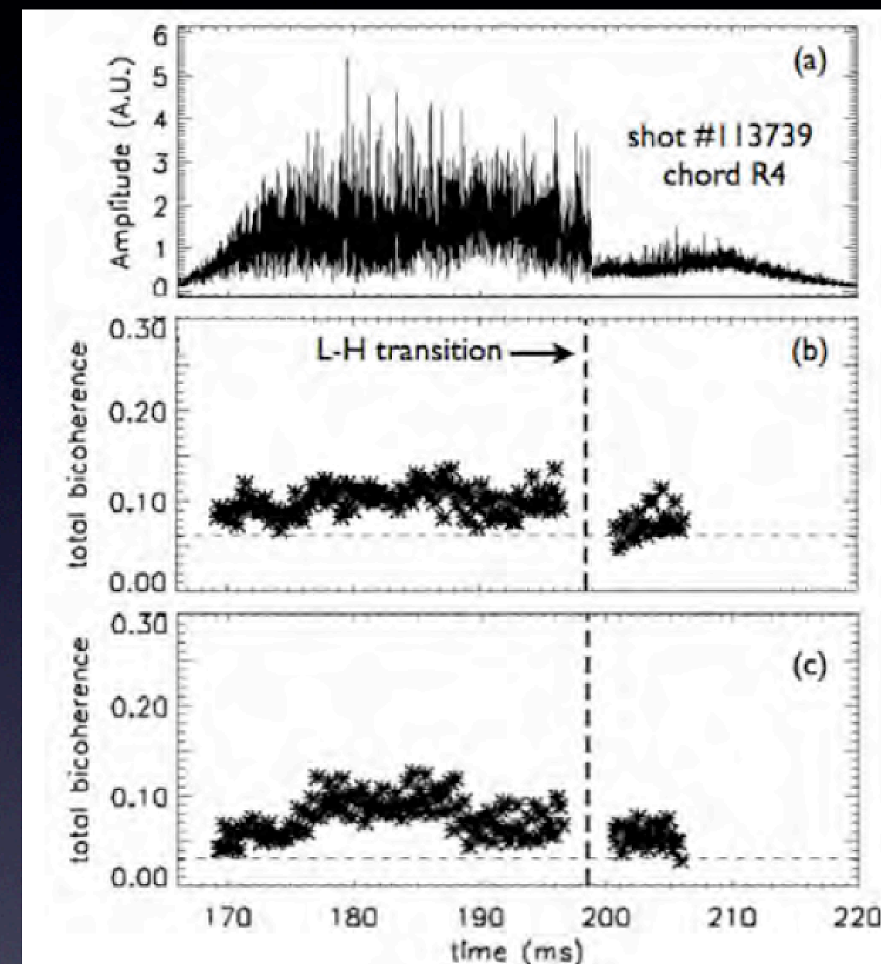
10
5
0
−5
−10
y (cm)
NO BIAS
Δt = −163μs
BIAS
20
22
24
26
28
30
x (cm)
20
22
24
26
28
30
x (cm)

Shear suppression of turbulence is accepted explanation of H-mode, but what drives the flow?

- Very important unsolved problem (future work for you?)
- Turbulence can self-regulate by nonlinearly driving flow (zonal flow, driven by Reynolds stress). Is this the L to H mechanism?
- Flows could spontaneously develop due to changes in poloidal flow damping [Shaing, et al show bifurcation]
- Radial electric field due to orbit loss, etc?
- Another important question: What sets the height of the pedestal? [This sets ultimate fusion performance!!]

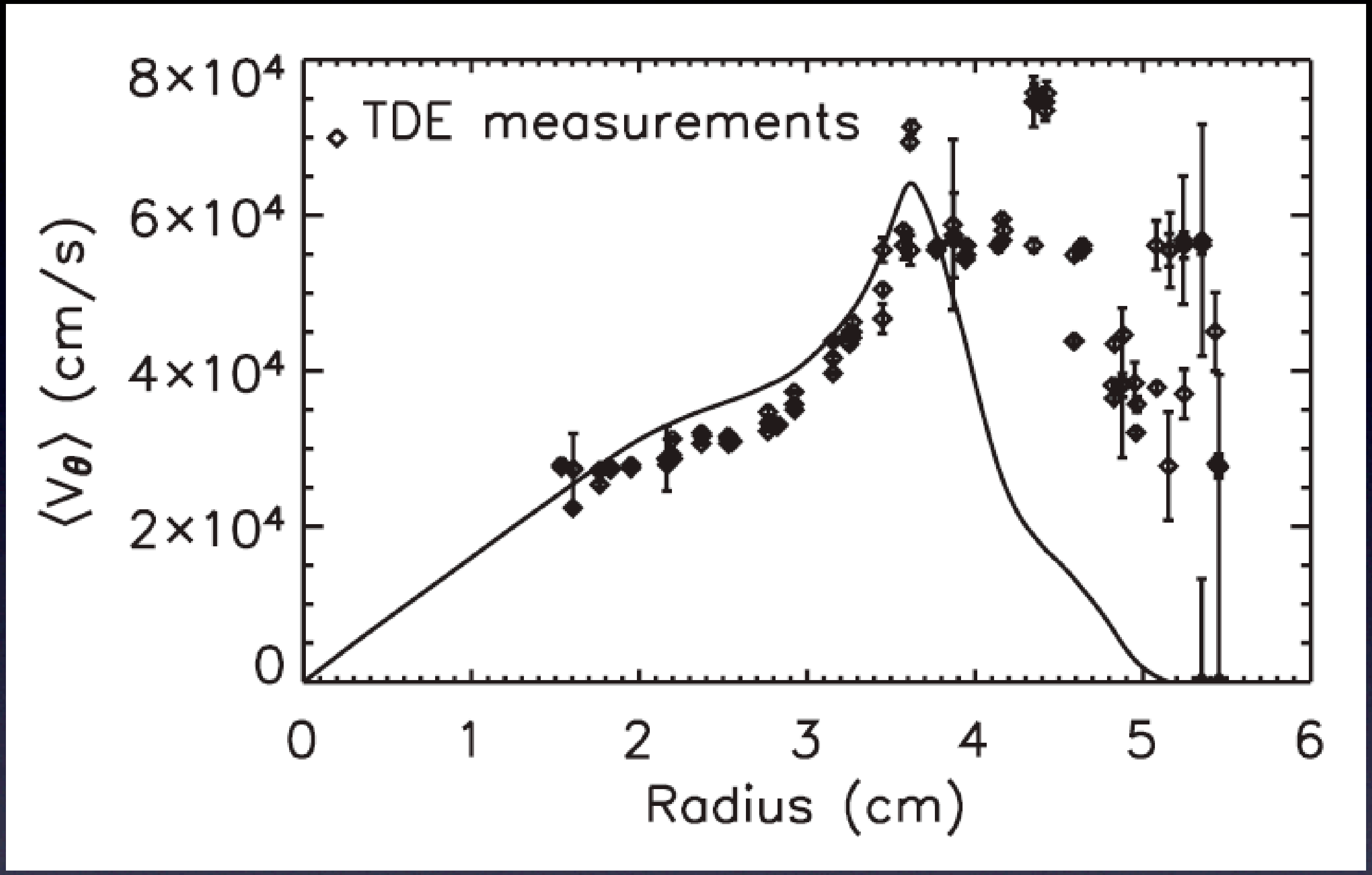
Conflicting data in tokamaks on turbulent driven flow





- DIII-D shows evidence at transition [Moyer, Tynan, et al], NSTX does not [White, Zweben, Burin, Carter, et al]

Data from small experiment shows strong evidence for turbulence driven flow



- CSDX [Holland, Tynan, et al] directly measured turbulent drive and compared to flow measurements (above)

Conclusion

- Answer to the original question: Why is ITER so darn big?
- To make confinement time large enough! Transport is roughly at the same rate as in smaller machines, but has further to go, meaning longer confinement time (dumb way to make a reactor work!)
- Challenge for you: understand and control turbulence and transport so that we can build smaller, more economical fusion plants